AD NUMBER: AD0826447
LIMITATION CHANGES
TO: Approved for public release; distribution is unlimited.
FROM: Distribution authorized to U.S. Defense agencies only; Administrative/Operational Use; 1 Dec 1967. Other requests shall be referred to the Army Chief of Engineers, Military Construction, Washington, DC 20315
AUTHORITY
OCE, D/A LTR, 23 JAN 1981

OCE NEMP PROGRAM

Development of Criteria for Protection of NIKE-X Power Plant and Facilities Electrical Systems Against Nuclear Electromagnetic Pulse Effects

PROTECTIVE MEASURES

1 December 1967

Submitted by:

E. R. UHLIG

Placed by:

Military Construction
Office of the Chief of Engineers
Department of the Army
Washington, D.C. 20315

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

CONTRACT NUMBER DA - 49 - 129 - ENG - 543

GENERAL ELECTRIC COMPANY
PITTSFIELD, MASS.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) General Electric Company 100 Woodlawn Avenue Pittsfield, Massachusetts 01201	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None

3. REPORT TITLE
OCE NEMP Program, Development of Criteria for Protection of NIKE-X Power Plant and Facilities Electrical Systems Against Nuclear Electromagnetic Pulse Effects, Protective Measures, 1 December 1967

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Protective Measures, 1 April 1967 to 1 December 1967

5. AUTHOR(S) (Last name, first name, initial)
Uhlig, Edward R.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
1 December 1967	412	21

8a. CONTRACT OR GRANT NO. DA-49-129-ENG-543 b. PROJECT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) 67U11
c. d.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None

10. AVAILABILITY/LIMITATION NOTICES
Each transmittal of this document outside the Department of Defense must have prior approval of Military Construction, Office of the Chief of Engineers, Department of the Army, Washington, D. C. 20315

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Military Construction, OCE Department of the Army Washington, D. C. 20315

13. ABSTRACT

This document represents the latest and most accurate information available for use in protecting NIKE-X power plants and facilities electrical systems against the effects of nuclear electromagnetic pulses. The information provides the current results of the OCE NEMP program for development of criteria. The information is written in criteria format, so that all or part of it may be extracted for use by agencies working with the NIKE-X Project Office in preparation of formal design criteria for the various major system components or categories such as power plant, technical facilities, missile farm, etc.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
EMP Effects						
Power System Protection						
Shielding						

INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. **GROUP:** Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

8a. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. **ORIGINATOR'S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. **AVAILABILITY/LIMITATION NOTICES:** Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

12. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. **ABSTRACT:** Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Unclassified
Security Classification

Report No. 67U11

Copy 64 of 100 Copies

OCE NEMP PROGRAM

Development of Criteria for Protection of NIKE-X Power Plant and Facilities Electrical Systems Against Nuclear Electromagnetic Pulse Effects

PROTECTIVE MEASURES

1 December 1967

Submitted by:

E. R. UHLIG

Placed by:

Military Construction
Office of the Chief of Engineers
Department of the Army
Washington, D.C. 20315

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

CONTRACT NUMBER DA - 49 - 129 - ENG - 543

GENERAL ELECTRIC COMPANY
PITTSFIELD, MASS.

TABLE OF CONTENTS

Table of Contents

Table of Contents

Table of Contents

Table of Contents

Table of Contents

Table of Contents

PRECEDING PAGE BLANK-NOT FILMED

LIST OF ILLUSTRATIONS

List of Illustrations
- page 2 -

List of Illustrations

List of Illustrations
- page 4 -

List of Illustrations

LIST OF TABLES

List of Tables

1.0 INTRODUCTION

This document represents the latest and most accurate information available for use in protecting NIKE-X power plants and facilities electrical systems against the effects of Nuclear Electromagnetic Pulses. The information provides the current results of the OCE NEMP Program for development of electrical power system protective measures. The information is written in criteria format so that all or part of it may be extracted for use by agencies working with the NIKE-X Project Office in preparation of formal design criteria for the various major system components or categories such as power plant, technical facilities, missile farm, etc.

1.1 Objectives

The overall objective of this document is to provide engineering information for the protection of NIKE-X power plants and facilities electrical systems against the effects of electromagnetic pulses. This objective has been met by properly combining the following techniques:

1. Study of state-of-the-art NEMP phenomenology.
2. Use of existing analytical and empirical approaches for the determination of shielding effectiveness of structures and enclosures.
3. Determination of NEMP effects upon and responses of interconnections, components, subsystems, and systems.
4. Conducting experiments and analyses to assess the effectiveness of protective measures in simulated NEMP field environments.

The material presented herein does not have as its objectives the generation of a system design, but rather the identification of electrical equipment, components, and subsystems which may require NEMP protection as well as the means and methods necessary to incorporate the protection requirements into the power system design as it is being formulated.

1.2 Identification of the Problem

The existence of electromagnetic field pulses produced by nuclear detonations has been recognized since the beginning of the use of nuclear weapons.

Such electromagnetic field pulses may induced harmful voltages and currents in structures and in electrical systems exposed to them. Obviously, systems at great distances away from nuclear detonations are exposed to weaker electromagnetic field pulses than systems close to the point of detonation. Historically, these pulsed electromagnetic fields and the accompanying induced currents and voltages caused measurement difficulties and other electrical problems during weapon test programs. As more knowledge concerning the possible magnitudes of the electrical effects became available, it was discovered that nuclear electromagnetic pulse (NEMP) induced electrical effects could impair performance, cause malfunctions, and/or damage electrical components of military and civilian systems.

Determination of the magnitude of NEMP induced voltages and currents, assessments of their effects upon electrical system performance and the provision of techniques and procedures for the control of the undesired NEMP effects with respect to power and other electrical systems are the purposes of this report.

1.3 Scope and Utilization of NEMP Protective Recommendations

This engineering information is basically being prepared for the architects and engineers who will be responsible for the electrical and constructional design specifications as well as site inspection. The scope and implementation of this information may best be illustrated by referring to Figure 1.1. Initially, the designer must be knowledgeable in three areas. These are:

1. the site environment specifications which detail the magnetic field magnitudes and other electromagnetic effects to which the site will be exposed.
2. the power system performance requirements which detail the maximum allowable overvoltages permitted.
3. the preliminary design concepts for the electrical power system.

These three inputs are combined, evaluated, and compared to the range of

protective recommendations incorporated in Section 2.0 for the power building and Section 3.0 for the facilities. If these protective recommendation sections are adaptable, then they can be used directly and the protection requirements given in Sections 2.0 and 3.0 apply. If the design requirements regarding site environment and system performance take on values which are not included in Sections 2.0 and 3.0, further analysis must be made to determine whether changes are necessary to meet the new requirements. The type of analysis which must be made is given in Section 4.0. If the analysis indicates that additional protection is necessary, Section 5.0 gives the information which permits the proper selection of the required protection technique.

Expansion and improvement of NEMP Protective Recommendations are continuing; any power system design questions involving NEMP effects that have not been answered adequately herein should be referred to the Office of the Chief of Engineers.

1.4 Site Characteristics

To most effectively apply these recommendations to the generation of a system design, data should be available giving the following electrical and geological characteristics of the site or sites selected.

1.4.1 Earth Corrosiveness

Determination of earth corrosiveness requires measurements of copper/copper sulphate ($Cu/CuSO_4$) half-cell potentials. Half-cell descriptions and measurement procedures are given in Section 10.0, Technical Reference Data.

1.4.2 Geological Characteristics

Sufficient geological information is required to identify the existence of rock strata or boulders which may affect ground resistance or hinder the installation of ground rods.

1.4.3 Water Table

Average depth of water table at site location should be determined.

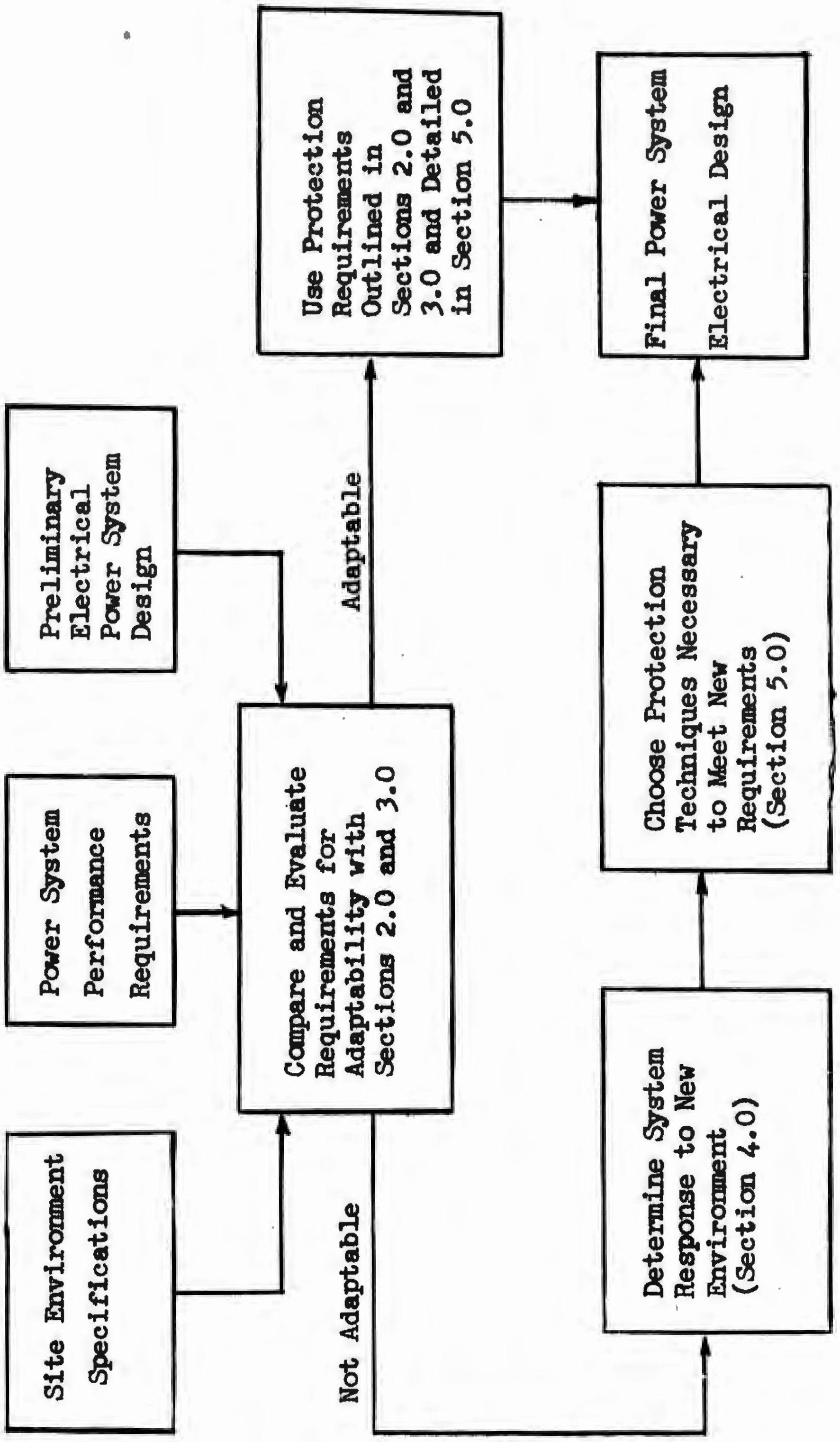


FIGURE 1.1 Scope and Use

2.0 POWER PLANT BUILDING PROTECTIVE RECOMMENDATIONS

2.1 Introduction

Studies and analyses made under the contract to date have resulted in the formulation of recommendations for the protection of the power building electrical system against NEMP effects. These recommendations are in the form of several alternate basic shielding schemes. These schemes have been formed from the following concepts:

1. Local Shielding deals with the shielding of items susceptible to NEMP on an individual basis. Since each susceptible item may have a different degree of susceptibility in a given environment, it is possible with this concept to define individual shielding requirements for any set of environmental conditions.
2. Group Shielding involves assembling NEMP susceptible items in the power building into functional groups and shielding these groups. This concept is particularly applicable to such areas as:
   a. control room
   b. primary switchgear area
   c. motor generator rooms or enclosures
   d. engine generator modules
   e. power plant cooling room
   f. boiler room
   g. station service room
   h. MSR cooling room
3. Overall Shielding, which employs a continuous shield enveloping the entire power plant building including incoming cable vaults and outgoing utility tunnels.

With each of these basic concepts there are various shielding techniques and construction arrangements (Section 5.0) which can be applied for implementing an NEMP protection system. Specific shielding "schemes", Section 2.2, based on particularly feasible structural arrangements have been

recommended. These specific shielding schemes for each of the foregoing concepts are described in Section 2.2. The individual schemes are composed of a standard set of protective measures, "building blocks", which are delineated in Section 2.3.

2.2 Shielding Schemes

The shielding schemes give specific requirements for power system items which require NEMP protection or construction features which may be required for NEMP protection of the system. The items treated in each of the specific schemes are:

1. control room
2. electrical raceways
3. electrical wiring
4. electrical equipment
5. enclosures
6. grounding
7. openings
8. penetrations
9. utility piping
10. power plant building

A shielding scheme is defined as a set of shielding requirements applying to the susceptible items in the electrical power system for a given environment. The shielding requirements for a susceptible item exposed to a given environment have been developed and evaluated over a range of environments and system performance levels. This has resulted in the formulation of shielding requirements (protective measure types) for each susceptible item. These protective measure types form the base for the development of shielding schemes each of which is a separate entity.

The shielding schemes presently under consideration are local, group, overall rebar, overall sheet steel with continuously welded seams, and overall sheet steel with spot welded seams. The environments are classified.

Brief narrative descriptions of the schemes are presented in the following. In addition, each scheme is presented in Table 2.1 in terms of the shielding requirements given as protective measure types necessary for each susceptible item. Underneath the shielding type designation, the section number directs the reader to the section in this report that presents in detail the protective measure.

2.2.1 Local Shielding

All items of electrical and electronic equipment are shielded on a separate basis. All equipment within the control room is treated as one susceptible "item".

In this scheme conduit, metal cable sheaths and armor, bus enclosures, and other specifically approved electrical raceways serve to shield the electrical wiring, while cabinets, cases, compartments, or consoles, etc. serve to shield susceptible electrical and/or electronic equipment. The principal advantages of this shielding scheme are the possibilities for selecting and grading attenuation levels to meet specified environmental conditions. The main disadvantages are the difficulty of insuring completeness of the shielding and coordinating all the levels of shielding that are required, particularly at openings and penetrations.

2.2.2 Group Shielding

Particular groups of functional equipment are shielded. Normally the shielding would be designed to afford the required NEMP protection for the most susceptible piece of equipment within the shield under a specified environment.

All electrical wiring outside of group shields would be contained within conduit, metal cable sheaths and armor, bus enclosures, or other specifically approved electrical raceways. Susceptible equipment outside group shielding would be shielded on an individual basis, as outlined in local shielding.

As advantages, this scheme offers possibilities for grading the

shielding attenuation as well as simplifying wiring for equipment within the shields. Also, its application is somewhat less expensive than overall shielding. The main disadvantage of this scheme is that group shielding design is influenced by relatively few pieces of particularly sensitive or susceptible equipment. However, in prescribing this type of shielding, the additional attenuation required to protect these items may be considered as a safety factor over and above the requirements for less susceptible items.

2.2.3 Overall Building Shielding by Solid Steel Sheets

Install 11 gauge solid steel sheets with continuously welded seams completely covering all surfaces of the power plant building to afford NEMP protection for all electrical and electronic equipment inside. A number of factors such as site corrosivity, construction methods, and the shielding attenuation levels required would have to be considered in selecting the dimensions and manner of application of this shielding.

Another scheme is listed which is a variation of this scheme, in that instead of sheet steel with continuously welded seams, 20 gauge sheet steel panels are utilized with seams spot welded at specified intervals. All other protective measure requirements are the same.

Within a high performance overall shield, no supplementary shielding would be necessary for equipment or wiring. However, all openings and penetrations into the building from outside, unshielded areas would be designed so as to minimize shielding degradation.

Overall building shielding offers important advantages in the placement of susceptible equipment and wiring anywhere inside the shield without sacrificing NEMP protection, as well as simplifying the installation of these items. Disadvantages of an overall sheet steel envelope include:

1. possible high installation and maintenance costs.
2. difficulties in making accurate initial and surveillance appraisals of overall shielding effectiveness.

3. permitting relatively few equipment items that are particularly susceptible to NEMP effects to dictate the shielding attenuation levels required in an entire building.

2.2.4 Ove: ll Building Shielding by Double Course Rebars

In thi scheme, some of the steel rebars normally used in the reinforced concrete building construction would be welded to form continuous rebar loops around specified building perimeters. To achieve attenuation levels comparable with those that can be obtained with sheet steel shielding, double course rebar application has been considered.

Within a high performance, carefully fabricated rebar shield incorporated in the power plant building construction, no supplementary shielding would be necessary for equipment. However, specialized treatments would be necessary to control the magnitude of currents flowing on all conduits and metal utility piping at building penetrations and openings into outside, unshielded areas.

An overall, double course rebar shield has the same advantages and disadvantages as other forms of overall shielding except for cost. Since rebars used for shielding serve also as reinforcing media, the only incremental costs chargeable to a rebar shielding scheme would be those for welding, special construction at penetrations and openings, and the additional inspections required.

2.3 Tabulated Shielding Schemes

Table 2.1 presents the details of the foregoing schemes in tabular form. The protective measure types following the table can be considered as building blocks and should other shielding schemes be formulated, they would be listed in a similar fashion.

TABLE 2.1

POWER BUILDING NEMP PROTECTIVE RECOMMENDATIONS

Environment →	(S)	(S)	(S)	(S)	(S)
Susceptible Item	Group	Local	Overall Rebar	Overall Sheet Steel Spot Weld	Overall Sheet Steel Cont. Weld
2.3.1 Control Room	Type A 2.3.1.1	Type A 2.3.1.1	Type B 2.3.1.2	Type C 2.3.1.3	Type C 2.3.1.3
2.3.2 Electrical Raceways	Type B 2.3.2.2	Type B 2.3.2.2	Type C 2.3.2.3	Type D 2.3.2.4	Type D 2.3.2.4
2.3.3 Electrical Wiring	Type B 2.3.3.2	Type B 2.3.3.2	Type C 2.3.3.3	Type D 2.3.3.4	Type D 2.3.3.4
2.3.4 Electrical Equipment	Type C 2.3.4.3	Type C 2.3.4.3	Type D 2.3.4.4	Type E 2.3.4.5	Type E 2.3.4.5
2.3.5 Enclosures	Type C 2.3.5.3	Type C 2.3.5.3	Type D 2.3.5.4	Type E 2.3.5.5	Type E 2.3.5.5
2.3.6 Grounding	Type A 2.3.6.1	Type A 2.3.6.1	Type B 2.3.6.2	Type C 2.3.6.3	Type C 2.3.6.3
2.3.7 Openings	Type A 2.3.7.1	Type A 2.3.7.1	Type A 2.3.7.1	Type A 2.3.7.1	Type A 2.3.7.1
2.3.8 Penetrations	Type A 2.3.8.1	Type A 2.3.8.1	Type A 2.3.8.1	Type B 2.3.8.2	Type B 2.3.8.2
2.3.9 Utility Piping	Type A 2.3.9.1	Type A 2.3.9.1	Type A 2.3.9.1	Type B 2.3.9.2	Type B 2.3.9.2
2.3.10 Power Plant Building	Type D 2.3.10.4	Type D 2.3.10.4	Type C 2.3.10.3	Type B 2.3.10.2	Type A 2.3.10.1

2.3.1.1 Control Room - Type A

1. The control room shall be completely shielded with solid sheet steel to provide at least 40 dB of attenuation between 10 kilohertz and 10 megahertz for the electrical and electronic equipment inside.
2. With the overall shielding provided above, electrical equipment, equipment enclosures, and electrical wiring in the control room have no additional shielding requirement. However, grounding of these equipments and enclosures shall follow the practices given under Grounding (Section 2.3.6).
3. Cable trays, if used within the shielded control room, have no shielding requirement; however, they shall be grounded to the control room internal ground ring, metal shielding of the control room, or grounded metal equipment enclosures.
4. Electrical raceway and metal utility piping penetrations into the control room shall be made in conformity with the requirements of Section 5.3.2.2. Non-metal piping penetrations shall be made through metal wave guide sleeves (Section 5.3.3.3).

2.3.1.2 Control Room - Type B

1. The control room within the overall rebar shielded building shall be completely shielded with solid sheet steel to provide at least 20 dB of attenuation between 10 kilohertz and 10 megahertz for the electrical and electronic equipment inside.
2. With the overall shielding provided above, electrical equipment, equipment enclosures, and electrical wiring in the control room have no additional shielding requirement. However, grounding of these equipments and enclosures shall follow the practices given under Grounding (Section 2.3.6).
3. Cable trays, if used within the shielded control room, have no shielding requirement; however, they shall be grounded to the

control room internal ground ring, metal shielding of the control room, or grounded metal equipment enclosures.

4. Electrical raceway and metal utility piping penetrations into the control room shall be made in conformity with the requirements of Section 5.3.2.2. Non-metal piping penetrations shall be made through metal wave guide sleeves (Section 5.3.3.3).

2.3.1.3 Control Room - Type C

1. The control room shielding requirement is provided by the overall building solid sheet steel.
2. Shielding requirements for electrical wiring, electrical raceways, electrical equipment, electrical equipment enclosures, and utility piping which are installed in the control room are provided by the overall building shield.

2.3.2.1 Electrical Raceways - Type A

1. Within sheet steel shielded areas such as the control room or other group shielded areas, conduits are not required for NEMP protection. Installation shall follow Corps of Engineers requirements.
2. Inside the building but outside of sheet steel shielded areas, electrical raceways have the following requirements:
   a. Electrical raceways shall be rigid steel or wrought iron conduit, one inch electrical trade size or larger.
   b. Conduits shall be continuous so that contained wiring is never directly exposed to NEMP fields.
   c. All conduits shall be threaded. If joints are not continuously welded after assembling the threaded joints, threads shall be coated with a conductive sealant before assembling (Section 5.3.2.1).
   d. Conduit joints at equipment enclosures and junction boxes must maintain the shielding integrity of the enclosure (Section 5.3.2.2).

e. All conduit bends shall be radiused in accordance with standard requirements for the particular size conduit used.

f. Conduit connections to equipment having flexible or vibrational requirements shall be made with mild steel continuous seam bellows having a wire braid covering. Approved types of special flexible conduit may be used such as conduit constructed as a liquid-tight, strip-wound flexible metal hose having a flexible galvanized steel core. The core may have a built-in copper ground and may have an extruded polyvinylchloride cover. It is UL and JIC approved for liquid-tight applications.

g. Conduit penetrations into shielded and non-shielded areas are covered under Penetrations.

3. Outside the building, conduits have the following additional requirements:

   a. Conduits are the only approved raceways and shall be rigid steel or wrought iron, two inch electrical trade size or larger. Condulets shall not be used. Conduit joints shall be threaded and welded.

   b. Conduit runs which must be placed above ground level shall:

      1) be grounded by connection to counterpoise or ground rods at buildings (Section 5.3.2.2).

      2) be grounded by a 10 foot ground rod at the point of exit from the earth if this exit is more than 50 feet from the structure penetration.

      3) be grounded by a direct connection to a 10 foot ground rod at intervals not exceeding 100 feet.

   c. Conduit runs which are completely buried and less than 500 ft. long need only be grounded at penetrations of other grounded structures. Conduit runs 500 ft. or longer shall be grounded

at one intermediate location for each 500 ft. of conduit run.

d. Conduit penetrations at structures or manholes shall maintain the shielding integrity of the conduit.

e. Conduit runs to non-hardened loads shall meet the same NEMP requirements as conduit runs to hardened loads.

2.3.2.2 Electrical Raceways - Type B

1. Within sheet steel shielded areas such as the control room or other group shielded areas, conduits are not required for NEMP protection. Installation shall follow Corps of Engineers requirements.

2. Inside the building but outside the sheet steel shielded areas, the following electrical raceways are permitted:

   a. rigid steel or wrought iron conduit, one inch electrical trade size or larger. Condulets may be used.

   b. rigid aluminum conduit or steel electrical metallic tubing (E.M.T.) for 120 volt and 480 volt circuits. Condulets may be used. Aluminum conduit may not be used where it comes in contact with concrete, earth, or moisture.

   c. armored, shielded power cable for 120 volt and 480 volt circuits (Section 2.3.3.2.3, Electrical Wiring).

3. Inside the building but outside the sheet steel shielded areas, electrical raceways have the following requirements:

   a. Electrical raceways and interlocked cable armor shall be continuous so that contained wiring is never directly exposed to NEMP fields.

   b. Standard conduit assembly practices shall be used. Threads must be cleaned before assembly. Thread compounds shall not be used.

   c. Electrical raceway joints at equipment enclosures and junction boxes must maintain the shielding integrity of the enclosure (Section 5.3.2.2).

d. All conduit bends shall be radiused in accordance with standard requirements for the particular size conduit used.

e. Electrical raceway connections to equipment having flexible or vibrational requirements shall be made with mild steel continuous seam bellows having a wire braid covering. Approved types of special flexible conduit may be used, such as conduit constructed as a liquid-tight, strip-wound flexible metal hose having a flexible galvanized steel core. The core may have a built-in copper ground and may have an extruded polyvinylchloride cover. It is UL and JIC approved for liquid-tight applications.

f. Electrical raceway penetrations into shielded and non-shielded areas are covered under Penetrations.

4. Outside the building, conduits have the following additional requirements:

   a. Conduits are the only approved raceways and shall be rigid steel or wrought iron, two inch electrical trade size or larger. Condulets shall not be used. Conduit joints shall be threaded and welded.

   b. Conduit runs which must be placed above ground level shall:

      1) be grounded by connection to counterpoise or ground rods at buildings (Section 5.3.2.2).

      2) be grounded by a 10 foot ground rod at the point of exit from the earth if this exit is more than 50 feet from the structure penetration.

      3) be grounded by a direct connection to a 10 foot ground rod at intervals not exceeding 100 feet.

   c. Conduit runs which are completely buried and less than 500 ft. long need only be grounded at penetrations of other grounded structures. Conduit runs 500 ft. or longer shall be grounded

at one intermediate location for each 500 ft. of conduit run.

d. Conduit penetrations at structures or manholes shall maintain the shielding integrity of the conduit.

e. Conduit runs to non-hardened loads shall meet the same NEMP requirements as conduit runs to hardened loads.

2.3.2.3 Electrical Raceways - Type C

1. Within the sheet steel shielded control room, conduits or other NEMP protection is not required. Installation shall follow Corps of Engineers requirements.

2. Inside the building but outside the sheet steel shielded control room, the following electrical raceways are permitted:

   a. rigid steel or wrought iron conduit, one inch electrical trade size or larger. Condulets may be used.

   b. standard metal conduits and steel electrical metallic tubing, both at least one inch electrical trade size or covered cable trays. Condulets may be used. Cable trays may be of expanded or punched metal with individual openings not larger than one square inch. Ladder type trays may also be used providing the openings comprise not more than 40% of the face area.

   c. armored, shielded power cable for 120 volt and 480 volt circuits (Section 2.3.3.2.3, Electrical Wiring).

3. Inside the rebar shielded building but outside the sheet steel shielded control room, the following conduit and other electrical raceway requirements apply:

   a. Electrical raceways and interlocked cable armor shall be continuous so that contained wiring is never directly exposed to NEMP fields.

   b. Standard assembly practices shall be used. Threads must be clean before assembly. Thread compounds shall not be used.

   c. Electrical raceway joints at equipment enclosures and junction

boxes must maintain the shielding integrity of the enclosure (Section 5.3.2.2).

d. All conduit bends shall be radiused in accordance with standard requirements for the particular size conduit used.

e. Electrical raceway connections to equipment having flexible or vibrational requirements shall be made with mild steel continuous seam bellows having a wire braid covering. Approved types of special flexible conduit may be used such as conduit constructed as a liquid-tight, strip-wound flexible metal hose having a flexible galvanized steel core. The core may have a built-in copper ground and may have an extruded polyvinyl-chloride cover. It is UL and JIC approved for liquid-tight applications.

f. Electrical raceway penetrations into shielded and non-shielded areas are covered under Penetrations.

4. Outside the building, conduits have the following additional requirements:

   a. Conduits are the only approved raceways and shall be rigid steel or wrought iron, two inch electrical trade size or larger. Condulets shall not be used. Conduit joints shall be threaded and welded.

   b. Conduit runs which must be placed above ground level shall:

      1) be grounded by connection to counterpoise or ground rods at buildings (Section 5.3.2.2).

      2) be grounded by a 10 foot ground rod at the point of exit from the earth if this exit is more than 50 feet from the structure penetration.

      3) be grounded by a direct connection to a 10 foot ground rod at intervals not exceeding 100 feet.

   c. Conduit runs which are completely buried and less than 500 ft.

long need only be grounded at penetrations of other grounded structures. Conduit runs 500 ft. or longer shall be grounded at one intermediate location for each 500 ft. of conduit run.

d. Conduit penetrations at structures or manholes shall maintain the shielding integrity of the conduit.

e. Conduit runs to non-hardened loads shall meet the same NEMP requirements as conduit runs to hardened loads.

2.3.2.4 Electrical Raceways - Type D

1. Conduits are not required in overall shielded areas. Standard construction and wiring support practices, as approved by the Corps of Engineers, may be followed.

2. Conduit penetrations of the overall shield are covered under Penetrations.

3. Conduits between the shielded building and remote areas such as cooling towers, fuel storage, and other similar power plant facilities must meet the following requirements:

   a. Conduits are the only approved raceways and shall be rigid steel or wrought iron, two inch electrical trade size or larger. Condulets should not be used. Conduit joints shall be threaded and welded.

   b. All conduit runs shall be continuous so that contained wiring is never directly exposed to an EMP field.

   c. Conduit joints at equipment enclosures must maintain the shielding integrity of the enclosure (Section 5.3.2.2).

   d. All conduit bends shall be radiused in accordance with standard requirements for the particular size conduit used.

   e. Conduit connections to equipment within buildings having flexible or vibrational requirements shall be made with a mild steel continuous seam bellows having a wire braid covering. Approved types of flexible conduit may be used such as conduit constructed

as a liquid-tight, strip-wound flexible metal hose having a flexible galvanized steel core. The core may have a built-in copper ground and may have a polyvinylchloride cover. It is UL and JIC approved for liquid-tight applications.

f. Conduit runs which must be placed above ground level shall:
   1) be grounded by connection to counterpoise or ground rods at buildings (Section 5.3.2.2).
   2) be grounded by a 10 foot ground rod at the point of exit from the earth if this exit is more than 50 feet from the structure penetration.
   3) be grounded by a direct connection to a 10 foot ground rod at intervals not exceeding 100 feet.

g. Conduit runs which are completely buried and less than 500 ft. long need only be grounded at penetrations of other grounded structures. Conduit runs 500 ft. or longer shall be grounded at one intermediate location for each 500 ft. of conduit run.

h. Conduit penetrations at structures or manholes shall maintain the shielding integrity of the conduit.

i. Conduit runs to non-hardened loads shall meet the same NEMP requirements as conduit runs to hardened loads.

2.3.3.1 Electrical Wiring - Type A

1. All electrical wiring in the electrical power system must be shielded by shielding methods which provide at least 40 dB of attenuation to a 10 kHz continuous magnetic field. Within sheet steel shielded areas, such as the control room or other group shielded areas, this attenuation is provided by the area shielding.

2.3.3.1.1 13,800 Volt Wiring

1. All open bus shall be enclosed in bus enclosures having at least 40 dB of shielding. The bus enclosure shall be grounded at the equipment and equipment enclosure where the bus terminates. Grounding can

be provided by the terminal equipment (Section 5.2.2.3.9).

2. Within the building, shielded, armored power cable may be used instead of wiring in conduit. Cable armor shall be the interlocking type and phase conductor shields shall be continuous overlapping tapes of copper, aluminum, or steel and shall form a continuously shielded system with the equipment or enclosure electrically connected to cable shields and armor at each end. Aluminum may not be used where it comes in contact with concrete, earth, or moisture. The terminal equipment must be connected to the internal ground ring (Section 5.2.2.3). Cable trays used to support shielded, armored cable shall be grounded to the nearest ground at both ends of the cable tray run. Any trough or ladder-type cable supporting structure may be used.
3. Unshielded power cable shall be routed in rigid steel or wrought iron conduit, one inch electrical trade size or larger. Condulets shall not be used.
4. Generator neutral shall be connected to its grounding device by an insulated, shielded lead. Shielding may be provided by the metal enclosure of the power leads or by a separate conduit (Section 5.2.2.3).
5. Connecting leads to surge sloping capacitors between generator terminals and ground shall be kept as short as possible. The surge sloping capacitors may be placed within the generator enclosure (Section 5.2.2.3.8).
6. In the shielded control room, there are no specific requirements for enclosing electrical wiring in conduit. Steel electrical metallic tubing may be used and condulets may be used with conduit. Wiring may be run in open cable trays.

2.3.3.1.2 4160 and 6900 Volt Wiring

1. All requirements for 13,800 volt circuit wiring apply to 4160 and 6900 volt wiring.

2.3.3.1.3 480 Volt Wiring

1. All open bus shall be enclosed in bus enclosures having at least 40 db [illegible] shielding. Enclosures should be grounded at the equipment and/or equipment enclosure where the bus terminates. Grounding can be provided by terminal equipment (Section 5.2.2.3.9).
2. In unshielded areas all power cable shall be routed in rigid steel or wrought iron conduit, one inch electrical trade size or larger. Condulets shall not be used. Armored, shielded power cable shall not be used.
3. In the shielded control room, there are no specific requirements for enclosing electrical wiring in conduit. Steel electrical metallic tubing may be used or condulets may be used with conduit. Wiring may be run in open cable trays.

2.3.3.1.4 208/120 Volt Wiring

1. The requirements for 480 volt circuits apply to 208/120 volt circuits wherever applicable.

2.3.3.1.5 Control Wiring

1. Control wiring shall be routed in rigid steel or wrought iron conduit not smaller than one inch electrical trade size. Separation between power and control wiring shall follow National Electrical Code or Corps of Engineers requirements. No condulets shall be used.

2.3.3.1.6 Communications Wiring

1. Same requirements as control wiring. This wiring shall be routed in conduit not smaller than one inch electrical trade size. Separation between power and communications wiring shall follow National Electrical Code or Corps of Engineers requirements.

2.3.3.1.7 Alarm and Monitoring Subsystems Wiring

1. Wiring for fire alarm and automatic fire extinguishing subsystems, temperature and pressure monitors, smoke, gas, and conduit

continuity detectors, and other similar subsystems shall be routed in rigid steel or wrought iron conduit not smaller than one inch electrical trade size.

2. Alarm systems which use distributed sensors such as long open wire for heat detection shall not be used except in totally metal shielded areas. Individual sensing units with wiring routed as stated in (1) above are recommended.

2.3.3.1.8 Additional Wiring Requirements

Outside the building, wiring has the following additional requirements:

1. Wiring shall be contained in rigid steel or wrought iron conduit, two inch electrical trade size or larger.
2. Power wiring shall have surge arresters installed on both hardened and non-hardened circuits. Installations shall be made at approved locations and by approved methods.
3. Each building or area should preferably have an independent alarm system or systems. Alarm system wiring between buildings and to a central monitoring location shall be for indication signals only. These signal indicating circuits should be isolated from the primary alarm subsystem by relays or transformers.

2.3.3.2 Electrical Wiring - Type B

1. All electrical wiring in the electrical power system must be shielded by shielding methods which provide at least 40 dB of attenuation to a 10 kHz continuous magnetic field. Within sheet steel shielded areas such as the control room or other group shielded areas, this attenuation is provided by the area shielding.

2.3.3.2.1 13,800 Volt Wiring

1. All bus shall be enclosed in bus enclosures having at least 40 dB of attenuation. The bus enclosure shall be grounded at the equipment and equipment enclosure where the bus terminates. Grounding can be provided by the terminal equipment (Section 5.2.2.3.9).

2. Within the building, shielded, armored power cable may be used instead of wiring in conduit. Cable armor shall be the interlocking type and phase conductor shields shall be continuous overlapping tapes of copper, aluminum, or steel and shall form a continuously shielded system with the equipment or enclosures electrically connected to cable shields and armor at each end. Aluminum may not be used where it comes in contact with concrete, earth, or moisture. The terminal equipment must be connected to the internal ground ring (Section 5.2.2.3). Cable trays used to support shielded, armored cable shall be grounded to the nearest ground at both ends of the cable tray run. Any trough or ladder-type cable supporting structure may be used.
3. Unshielded cable shall be routed in rigid steel or wrought iron conduit, one inch electrical trade size or larger. Condulets may be used.
4. Generator neutral shall be connected to its grounding device by an insulated, shielded lead. Shielding may be provided by the metal enclosure of the power leads or by a separate conduit (Section 5.2.2.3).
5. Connecting leads to surge sloping capacitors between generator terminals and ground shall be kept as short as possible. The surge sloping capacitors may be placed within the generator enclosure (Section 5.2.2.3.8).
6. In the shielded control room, there are no specific requirements for enclosing electrical wiring in conduit. Steel electrical metallic tubing may be used and condulets may be used with conduit. Wiring may be run in open cable trays.

2.3.3.2.2 4160 and 6900 Volt Wiring

1. All requirements for 13,800 volt circuit wiring apply to 4160 and 6900 volt wiring.

2.3.3.2.3 480 Volt Wiring

1. All bus shall be enclosed in bus enclosures having at least 40 dB of attenuation and should be grounded at the equipment and equipment enclosure where the bus terminates. Grounding can be provided by terminal equipment (Section 5.2.2.3.9).
2. In the shielded control room, there are no specific requirements for enclosing electrical wiring in conduit. Steel electrical metallic tubing may be used or condulets may be used with conduit. Wiring may be run in open cable trays.

Type B electrical wiring for 480 volts permits the following:

3. Power wiring for unshielded cable may be routed in aluminum conduit or steel electrical metallic tubing (E.M.T.). Condulets are permitted on these circuits.
4. Armored, shielded power cable may also be used. Cable armor shall be the interlocking type and phase conductor shields shall be continuous overlapping tapes of copper, aluminum, or steel and shall form a continuously shielded system with the equipment or enclosure electrically connected to the cable shields and armor at each end. Aluminum may not be used where it comes in contact with concrete, earth, or moisture. Mineral-insulated, metal-sheathed cable (MI) or other such cable types which are covered by a seamless metallic tubing may also be used. Cable trays for this armored cable have no shielding requirement except to be grounded at both ends of the cable tray run.

2.3.3.2.4 208/120 Volt Wiring

1. The requirements for 480 volt circuits apply to 208/120 volt circuits.

2.3.3.2.5 Control Wiring

1. Control wiring shall be routed in rigid steel or wrought iron conduit not smaller than one inch electrical trade size. Separation

between power and control wiring shall follow National Electrical Code or Corps or Engineers requirements. No condulets shall be used.

2.3.3.2.6 Communications Wiring

1. Same requirements as control wiring. This wiring shall be routed in conduit not smaller than one inch electrical trade size. Separation between power and communications wiring shall follow National Electrical Code or Corps or Engineers requirements.

2.3.3.2.7 Alarm and Monitoring Subsystems Wiring

1. Wiring for fire alarm and automatic fire extinguishing subsystems, temperature and pressure monitors, smoke, gas, conduit continuity detectors, and other similar subsystems shall be routed in rigid steel or wrought iron conduit not smaller than one inch electrical trade size.
2. Alarm systems which use distributed sensors such as long open wire for heat detection shall not be used except in totally metal shielded areas. Individual sensing units with wiring routed as stated in (1) above are recommended.

2.3.3.2.8 Additional Wiring Requirements

Outside the building, wiring has the following additional requirements:

1. Wiring shall be contained in rigid steel or wrought iron conduit, two inch electrical trade size or larger.
2. Power wiring shall have surge arresters installed on both hardened and non-hardened circuits. Installations shall be made at approved locations and by approved methods.
3. Each building or area should preferably have an independent alarm system or systems. Alarm system wiring between buildings and to a central monitoring location shall be for indication signals only. These signal indicating circuits should be isolated from the primary alarm subsystem by relays or transformers.

2.3.3.3 Electrical Wiring - Type C

1. All electrical wiring in the electrical power system must be shielded by shielding methods which provide at least 40 dB of attenuation to a 10 kHz continuous magnetic field. Within sheet steel shielded areas, such as the control room, this attenuation is provided by the combined shielding of the rebars and control room shields. In areas shielded by rebar shielding, the following electrical wiring requirements apply.

2.3.3.3.1 13,800 Volt Wiring

1. All bus shall be enclosed in standard bus enclosures. The bus enclosure shall be grounded at the equipment and equipment enclosure where the bus terminates. Grounding can be provided by the terminal equipment (Section 5.2.2.3.9).
2. Within the building, shielded, armored power cable may be used instead of wiring in conduit. Cable armor shall be the interlocking type and phase conductor shields shall be continuous overlapping tapes of copper, aluminum, or steel and shall form a continuously shielded system with the equipment or enclosures electrically connected to cable shields and armor at each end. Aluminum may not be used where it comes in contact with concrete, earth, or moisture. The terminal equipment must be connected to the internal ground ring (Section 5.2.2.3). Cable trays used to support shielded, armored cable shall be grounded to the nearest ground at both ends of the cable tray run. Any trough or ladder-type cable supporting structure may be used.
3. Unshielded power cable shall be routed in standard metal conduit, E.M.T., or covered cable trays. (Cable tray specifications are given in Section 2.3.2.3.)
4. Generator neutral shall be connected to its grounding device by an insulated, shielded lead. Shielding may be provided by the

metal enclosure of the power leads or by a separate conduit (Section 5.2.2.3).

5. Connecting leads to surge sloping capacitors between generator terminals and ground shall be kept as short as possible. The surge sloping capacitors may be placed within the generator enclosure (Section 5.2.2.3.8).
6. In the shielded control room, there are no specific requirements for enclosing electrical wiring in conduit. Standard wiring practices may be used.

2.3.3.3.2 4160 and 6900 Volt Wiring

1. All requirements for 13,800 volt wiring apply to 4160 and 6900 volt wiring.

2.3.3.3.3 480 Volt Wiring

1. All bus shall be enclosed in standard bus enclosures which should be grounded at the equipment and equipment enclosure where the bus terminates. Grounding can be provided by terminal equipment (Section 5.2.2.3.9).
2. Unshielded power cable shall be routed in metal conduit, E.M.T., or covered cable trays.
3. Armored, shielded power cable may be used. Cable armor shall be the interlocking type and phase conductor shields shall be continuous overlapping tapes of copper,aluminum, or steel and shall form a continuously shielded system with the equipment or enclosure electrically connected to the cable shields and armor at each end. Aluminum may not be used where it comes in contact with concrete, earth, or moisture. Cable trays supporting these cables shall be grounded at each end of the cable tray run.
4. In the shielded control room, there are no specific requirements for enclosing electrical wiring in conduit. Standard wiring practices may be used.

2.3.3.3.4 208/120 Volt Wiring

1. The requirements for 480 volt circuits apply to 208/120 volt circuits.

2.3.3.3.5 Control Wiring

1. Control wiring shall be routed in standard metal conduit, E.M.T., or covered cable trays. Separation between power and control wiring shall follow National Electrical Code or Corps of Engineers requirements.

2.3.3.3.6 Communications Wiring

1. Same requirements as control wiring.

2.3.3.3.7 Alarm and Monitoring Subsystem Wiring

1. Wiring for fire alarm and automatic fire extinguishing subsystems, temperature and pressure monitors, smoke, gas, conduit continuity detectors, and other similar subsystems shall be routed in standard metal conduit, E.M.T., or covered metal cable trays.
2. Alarm systems which use distributed sensors such as long open wire for heat detection shall not be used except in totally metal shielded areas or within conduits. Individual sensing units with wiring routed as stated in (1) above are recommended.

2.3.3.3.8 Additional Wiring Requirements

Outside the building, wiring has the following additional requirements:

1. Wiring shall be contained in rigid steel or wrought iron conduit, two inch electrical trade size or larger.
2. Power wiring shall have surge arresters installed on both hardened and non-hardened circuits. Installations shall be made at approved locations and by approved methods.
3. Each building or area should preferably have an independent alarm system or systems. Alarm system wiring between buildings and to a central monitoring location shall be for indication signals only. These signal indicating circuits should be isolated from the primary alarm subsystem by relays or transformers.

2.3.3.4 Electrical Wiring - Type D

1. All electrical wiring must be shielded by a manner which provides at least 40 dB of attenuation to a 10 kHz continuous magnetic field. Within the building this attenuation may be provided by the overall building steel sheet covering.
2. Power wiring within the shielded building has no shielding requirement. Installation shall be in accordance with Corps of Engineers requirements.
3. Communications, alarm, monitoring, and other similar wiring installations shall be in accordance with Corps of Engineers requirements.
4. Outside the building, wiring has the following additional requirements:
   a. Wiring shall be contained in rigid steel or wrought iron conduit, two inch electrical trade size or larger.
   b. Power wiring shall have surge arresters installed on both hardened and non-hardened circuits. Installation shall be made at approved locations and by approved methods.
   c. Each building or area should preferably have an independent alarm system or systems. Alarm system wiring between buildings and to a central monitoring location shall be for indication signals only. These signal indicating circuits should be isolated from the primary alarm subsystem by relays or transformers.

2.3.4.1 Electrical Equipment - Type A

1. Electrical equipment located in the sheet steel shielded control room or other similarly group shielded areas have no additional shielding requirements. The necessary shielding will be provided by the area shield. Electrical equipment located outside shielded areas shall be shielded as follows:

a. Electric motors and generators require at least 14 dB of shielding. Electric motor and generator housings which meet dripproof requirements as defined in MIL-STD-108E will satisfy this shielding requirement.

b. Electrical equipment such as dry-type transformers and dry-type regulators require at least 30 dB of shielding. Liquid-filled transformers and regulators require metal enclosures for primary and secondary bushings having an attenuation level of at least 34 dB.

c. Dry-type transformers feeding lighting loads require at least 10 dB of shielding.

d. All power system transformers except metering transformers shall have grounded metallic electrostatic shields between high voltage and low voltage windings.

e. Relays with operating coils connected directly to power circuits such as generator protective relays shall be housed in metal enclosures. At least 34 dB of shielding attenuation is required at the relay regardless of its location within the enclosure. A shielded control room, or other equipment enclosure providing equivalent shielding at the relay, will satisfy this requirement.

f. Equipment and components in grounded metal containers such as bus selector circuit breakers and electronic components for prime mover governor control and automatic synchronization will require supplementary shielding. These shall be housed in metal enclosures having at least 20 dB of shielding.

g. Meters and relays in control circuits isolated from power circuitry by transformers or other coupling components shall be mounted flush with enclosure or panel outer surfaces. They shall not be surface mounted or exposed. Such equipment shall require approximately 20 dB of attenuation which should be

provided by the metal enclosure in which the meter or relay is mounted.

h. Susceptible equipment not in grounded metal containers, such as electronic components and sensitive relays in prime mover control, monitoring, and protective subsystems, shall have at least 34 dB of shielding.

i. Instrumentation and control portions of the air supply, exhaust, and ventilating subsystems having susceptible relays and electronic equipment shall have at least 34 dB of shielding.

j. Generators should be connected to their associated switchgear or module transformer by a bus assembled in a metal bus enclosure having 34 dB of shielding and grounded at both ends or by shielded, armored cable with shields and armor grounded at both ends (Section 5.2.2.3.8).

k. At each generator, surge sloping capacitors shall be installed between phase terminals and ground. Surge sloping capacitors are also required on motors connected to the primary bus (Sections 5.3.1.5 and 5.2.2.3.8).

l. For electrical equipment within the shielded control room, there are no specific NEMP shielding requirements.

m. Electrical equipment housings shall be grounded to an internal ground ring (Section 5.2.2.3).

n. Electrical or electronic equipment in the sheet steel shielded control room will have the necessary shielding requirements provided by the control room shield.

2.3.4.2 Electrical Equipment - Type B

1. Electrical equipment located in the sheet steel shielded control room or similarly group shielded areas have no additional shielding requirements. The necessary shielding will be provided by the area shield. Electrical equipment located outside the shielded

areas shall be shielded as follows:

a. Electric motors and generators require no additional shielding.

b. Electrical equipment such as dry-type transformers and dry-type regulators require at least 16 dB of shielding. Liquid-filled transformers and regulators require metal enclosures for primary and secondary bushings having an attenuation level of at least 20 dB.

c. Dry-type transformers feeding lighting loads require no additional shielding.

d. All power system transformers except metering transformers shall have grounded metallic electrostatic shields between high voltage and low voltage windings.

e. Relays with operating coils connected directly to power circuits such as generator protective relays shall be housed in metal enclosures. At least 20 dB of shielding attenuation is required at the relay regardless of its location within the enclosure. A shielded control room, or other equipment enclosure providing equivalent shielding at the relay, will satisfy this requirement.

f. Equipment and components in grounded metal containers such as bus selector circuit breakers and electronic components for prime mover governor control and automatic synchronization will require supplementary shielding. These shall be housed in metal enclosures having at least 6 dB of shielding.

g. Meters and relays in control circuits isolated from power circuitry by transformers or other coupling components shall be mounted flush with enclosure or panel outer surfaces. They shall not be surface mounted or exposed. Such equipment shall require approximately 6 dB of attenuation which should be provided by the metal enclosure in which the meter or relay is mounted.

h. Susceptible equipment not in grounded metal containers such as electronic components and sensitive relays in prime mover control, monitoring and protective subsystems shall have at least 20 dB of shielding.

i. Instrumentation and control portions of the air supply, exhaust, and ventilating subsystems having susceptible relays and electronic equipment shall have at least 20 dB of shielding.

j. Generators should be connected to their associated switchgear or module transformer by a bus assembled in a metal bus enclosure having 34 dB of shielding and grounded at both ends or by shielded, armored cable with shields and armor grounded at both ends (Section 5.2.2.3.8).

k. At each generator, surge sloping capacitors shall be installed between phase terminals and ground. Surge sloping capacitors are also required on motors connected to the primary bus (Sections 2.3.3.1.1 and 5.2.2.3.8).

l. For electrical equipment within the shielded control room, there are no specific NEMP shielding requirements.

m. Electrical equipment housings shall be grounded to an internal ground ring (Section 5.2.2.3).

n. Electrical or electronic equipment in the sheet steel shielded control room will have the necessary shielding requirements provided by the control room shield.

2.3.4.3 Electrical Equipment - Type C

1. Electrical equipment located in the sheet steel shielded control room or similarly group shielded areas have no additional shielding requirements. The necessary shielding will be provided by the area shield. Electrical equipment located outside the shielded areas will be shielded as follows:

a. Electric motors and generators require no additional shielding.

b. Electrical equipment such as dry-type transformers and dry-type regulators require at least 10 dB of shielding. Liquid-filled transformers and regulators require metal enclosures for primary and secondary bushings having an attenuation of at least 14 dB.

c. Dry-type transformers feeding lighting loads require no additional shielding.

d. All power system transformers except metering transformers shall have grounded metallic electrostatic shields between high voltage and low voltage windings.

e. Relays with operating coils connected directly to power circuits, such as generator protective relays, shall be housed in metal enclosures. At least 14 dB of shielding attenuation is required at the relay regardless of its location within the enclosure. A shielded control room, or other equipment enclosure providing equivalent shielding at the relay, will satisfy this requirement.

f. Equipment and components in grounded metal containers such as bus selector circuit breakers and electronic components for prime mover governor control and automatic synchronization will require no supplementary shielding.

g. Meters and relays in control circuits isolated from power circuitry by transformers or other coupling components shall be mounted flush with enclosure or panel outer surfaces. They shall not be surface mounted or exposed. All the shielding necessary is provided by the metal enclosure in which the meter or relay is mounted.

h. Susceptible equipment not in grounded metal containers such as electronic components and sensitive relays in prime mover control, monitoring, and protective subsystems shall have at least 14 dB of shielding.

i. Instrumentation and control portions of the air supply, exhaust, and ventilating subsystems having susceptible relays and electronic equipment shall have at least 14 dB of shielding.

j. Generators should be connected to their associated switchgear or module transformer by a bus assembled in a metal bus enclosure having 34 dB of shielding and grounded at both ends or by shielded, armored cable with shields and armor grounded at both ends (Section 5.2.2.3.8).

k. At each generator, surge sloping capacitors shall be installed between phase terminals and ground. Surge sloping capacitors are also required on motors connected to the primary bus (Sections 2.3.1.1 and 5.2.2.3.8).

l. For electrical equipment within the shielded control room, there are no specific NEMP shielding requirements.

m. Electrical equipment housings shall be grounded to an internal ground ring (Section 5.2.2.3).

n. Electrical or electronic equipment in the sheet steel shielded control room will have the necessary shielding requirements provided by the control room shield.

2.3.4.4 Electrical Equipment - Type D

1. No special shielding requirements are necessary for electrical equipment such as motors, generators, and dry-type transformers and regulators having no external bushings. This type of equipment shall be assembled so that electrical continuity exists between all enclosure or housing parts. Transformers and regulators require metal enclosures for external primary and secondary bushings.

2. Dry-type transformers feeding lighting loads require no additional shielding.

3. All power system transformers except metering transformers shall

have grounded metallic electrostatic shields between high voltage and low voltage windings.

4. Electrical equipment such as switchgear, motor control centers, and equipment of this type normally contained in an enclosure shall be housed in a six-sided enclosure having at least five metal sides. One of the five sides may be an access door. All metal surfaces shall be electrically interconnected and grounded. Louvers or other standard construction for ventilation purposes may be used. Electrical raceways shall enter the enclosure through a metal surface. Electrical raceways which for constructional purposes must enter through the open bottom, must enter through a patch plate which is electrically connected to the enclosure.
5. Generators should be connected to their associated switchgear or module transformer by a bus assembled in a standard metal bus enclosure grounded at both ends or by shielded, armored cable with shields and armor grounded at both ends (Section 5.2.2.3.8).
6. At each generator, surge sloping capacitors shall be installed between phase terminals and ground. Surge sloping capacitors are also required on motors connected to the primary bus (Sections 2.3.3.1 and 5.2.2.3.8).
7. For electrical equipment within the shielded control room, there are no specific NEMP shielding requirements.
8. Electrical equipment housings shall be grounded to an internal ground ring (Section 5.2.2.3).
9. Electrical or electronic equipment in the sheet steel control room will have the necessary shielding requirements provided by the control room shield.

2.3.4.5 Electrical Equipment - Type E

1. Electrical and electronic equipment located within the overall building sheet steel shield have no additional shielding

requirements. The necessary shielding will be provided by the overall building shield.

2. All power system transformers except metering transformers shall have grounded metallic electrostatic shields between high voltage and low voltage windings.
3. At each generator, surge sloping capacitors shall be installed between phase terminals and ground. Surge sloping capacitors are also required on motors connected to the primary bus (Sections 2.3.3.1 and 5.2.2.3.8).
4. All electrical equipment shall be connected to an internal ground ring.

2.3.5.1 Enclosures - Type A

1. Within sheet steel shielded areas, such as the control room or other group shielded areas, enclosures shall be connected to an internal ground ring.
2. Outside of shielded areas, the following additional NEMP requirements apply:
   a. Enclosures for open wiring used as a substitute for conduit and interconnections shall provide at least 40 dB of attenuation.
   b. Junction boxes, wherever used to house open wiring, shall be totally enclosed and provide at least 34 dB of shielding (Section 5.3.7).
   c. Enclosures and cabinets having open wiring shall provide at least 34 dB of shielding.
   d. Equipment enclosures shall be connected to an internal ground ring (Section 5.2.2.3).

2.3.5.2 Enclosures - Type B

1. Within sheet steel shielded areas, such as the control room or other group shielded areas, enclosures shall be connected to an internal ground ring.

2. Outside shielded areas, the following additional NEMP requirements apply:
   a. Enclosures for open wiring used as a substitute for conduit and interconnections shall provide at least 40 dB of attenuation.
   b. Junction boxes, wherever used to house open wiring, shall be totally enclosed and provide at least 20 dB of shielding (Section 5.3.7).
   c. Enclosures and cabinets having open wiring shall provide at least 20 dB of shielding.
   d. Equipment enclosures shall be connected to an internal ground ring (Section 5.2.2.3).

2.3.5.3 Enclosures - Type C

1. Within sheet steel shielded areas, such as the control room or other group shielded areas, enclosures shall be connected to an internal ground ring.
2. Outside shielded areas, the following additional NEMP requirements apply:
   a. Enclosures for open wiring used as a substitute for conduit and interconnections shall provide at least 40 dB of attenuation.
   b. Junction boxes, wherever used to house open wiring, shall be totally enclosed and provide at least 14 dB of shielding (Section 5.3.7).
   c. Enclosures and cabinets having open wiring shall provide at least 14 dB of shielding.
   d. Equipment enclosures shall be connected to an internal ground ring (Section 5.2.2.3).

2.3.5.4 Enclosures - Type D

1. Within the sheet steel shielded control room in a rebar shielded building, enclosures shall be grounded to the internal ground ring.

2. Outside the shielded control room but within the rebar shielded building, the following NEMP requirements apply:
   a. Enclosures for open wiring used as a substitute for conduit and interconnections shall provide at least 20 dB of attenuation.
   b. Junction boxes, wherever used to house open wiring, shall be totally enclosed and may be of standard construction.
   c. Enclosures and cabinets having open wiring shall be of standard construction having five or six metal sides. Electrical continuity shall be maintained between all metal sides. Louvers or other standard construction for ventilation purposes may be used. Electrical raceways shall enter the enclosure through a metal surface. Electrical raceways which must enter through an open bottom, must enter through a patch plate which is electrically connected to the enclosure.
   d. Equipment enclosures shall be connected to an internal ground ring (Section 5.2.2.3).

2.3.5.5 Enclosures - Type E

1. Inside a sheet steel shielded building, electrical equipment enclosures, electrical wiring, junction boxes, and other similar electrical component housings have no shielding requirement. The necessary shielding is provided by the overall building shield.
2. All enclosures housing electrical equipment shall be connected to an internal ground ring.

2.3.6.1 Grounding - Type A

1. The building shall be provided with an external grounding system consisting of a counterpoise grid interconnected with ground rods (Sections 5.2.2.1 and 5.2.2.2).
2. Construction rebars shall be grounded as prescribed in Section 5.2.2.2.

3. Rooms within the building which contain electrical or electronic equipment shall be provided with an internal ground ring to effectively ground this equipment (Section 5.2.2.3).
4. Hardware, piping, conduits, structures, ducts, plenums, equipment, equipment enclosures, and other metal parts may be grounded by a multiple point grounding system (Section 5.2.2.3 and 5.2.2.4).
5. Electric power circuits should follow conventional grounding practices. Neutral grounding shall be made by means of a separate connection to the internal ground ring or to a separate neutral grounding bus (Section 5.2.2.3.10).
6. Cable trays should be grounded to the internal ground ring or to grounded metal equipment wherever cable trays are permitted.

2.3.6.2 Grounding - Type B

1. The rebar shielded building shall be provided with an external grounding system consisting of a counterpoise grid interconnected with ground rods (Sections 5.2.2.1 and 5.2.2.2).
2. Shielding rebars shall be grounded as prescribed in Section 5.2.2.2.
3. The building rebar shielding shall be interconnected with the counterpoise ground grid at the intervals specified in Section 5.2.2.2.
4. Rooms within the building which contain electrical or electronic equipment shall be provided with an internal ground ring to effectively ground this equipment. The internal ground ring shall be connected to the counterpoise (Section 5.2.2.3).
5. Hardware, piping, conduits, structures, ducts, plenums, equipment, equipment enclosures, and other metal parts must be effectively grounded to the nearest practical location on the grounding system (Sections 5.2.2.3 and 5.2.2.4).
6. Electric power circuits should follow conventional grounding practices. Neutral grounding shall be made by means of a separate

connection to the internal ground ring or to a separate neutral grounding bus (Section 5.2.2.3.10).

7. Cable trays should be grounded to the internal ground ring or to grounded metal equipment wherever cable trays are permitted.

2.3.6.3 Grounding - Type C

1. The sheet steel shielded building shall be provided with an external grounding system consisting of a counterpoise around the building periphery and ground rods (Sections 5.2.2.1 and 5.2.2.2).
2. The overall building sheet steel shall be grounded as prescribed in Section 5.2.2.2.
3. Rooms within the building which contain electrical or electronic equipment shall be provided with an internal ground ring to effectively ground this equipment. The internal ground ring shall be connected to the counterpoise (Section 5.2.2.3).
4. Hardware, piping, conduits, structures, ducts, plenums, equipment, equipment enclosures, and other metal parts must be effectively grounded to the nearest practical location on the grounding system (Sections 5.2.2.3 and 5.2.2.4).
5. Electric power circuits should follow conventional grounding practices. Neutral grounding shall be made by means of a separate connection to the internal ground ring or to a separate neutral grounding bus (Section 5.2.2.3.10).
6. Cable trays should be grounded to the internal ground ring or to grounded metal equipment wherever cable trays are permitted.

2.3.7.1 Openings - Type A

1. Openings in shielded buildings, rooms, and enclosures shall be designed so as not to degrade the intended shielding of the building, room, or enclosure (Sections 5.3.3.3, 5.3.4.3, 5.3.5.3, and 5.3.7.3).
2. Openings in shielded buildings and rooms used for personnel access

shall be of the wave guide type. Alternatively, commercially constructed doors may be used. In either case, the shielding integrity required in Item (1) above shall be provided (Sections 5.3.3.3, 5.3.4.3, 5.3.5.3, and 5.3.7.3).

3. Openings such as louvers are permitted for enclosures of equipment and components provided the attenuation requirements of the enclosure are met.

2.3.8.1 Penetrations - Type A

1. Conduit penetrations shall be made by the methods prescribed in Section 5.3.2.2.
2. Conduit penetrating the building should preferably enter and leave at the ground grid level and be connected to the ground grid at this point. For conduit entering at heights not greater than one half the total building height, steel grounding plates of proper dimension shall be used to connect conduit to counterpoise. For conduit entering at heights greater than one half the total building height, the width of the grounding plate should equal that used for conduit entering at one half total height and an auxiliary wire mesh screen having a width equal to the steel plate should be connected between the top of the steel plate and extend over the top of the building and connect to conduit leaving the building on any of the other three sides. Typical cases are illustrated in Section 5.3.2.2.
3. Conduits penetrating the sheet steel shielded utility access tunnel may penetrate the tunnel at any point. Penetration methods are given in Section 5.3.2.2.
4. Conduits penetrating an unshielded room containing electrical or electronic equipment must be connected to the internal ground ring by at least a No. 6 AWG copper bonding strap or to grounded metal equipment enclosures. For conduit entering a solid metal plate

shielded wall, the conduit shall be welded or brazed to the plate (Section 5.3.2.2).

5. Metal utility pipe penetrations are treated the same as conduits (Section 5.3.2.2).
6. Non-metal pipe penetrations into shielded areas shall be made through a wave guide type sleeve (Section 5.3.2.2). Non-metal pipe penetrations into unshielded areas require no special treatment.
7. Metal ducts, plenums, and similar type penetrations into shielded areas shall be designed as wave guide type penetrations which maintain the shielding integrity of the shielded volume. If these ducts or plenums form completely shielded enclosures having the required attenuation level with the terminating equipment, no wave guide provisions are necessary (Sections 5.3.3.3, 5.3.4.3, 5.3.5.3, and 5.3.7.3).
8. Metal ducts and plenums which penetrate unshielded areas shall be electrically connected to grounded equipment at each end. Non-metal ducts and plenums penetrating such areas have no EMP design restrictions.
9. Cable tray penetrations wherever cable trays are permitted shall be made by prescribed methods.

2.3.8.2 Penetrations - Type B

1. Conduit penetrations shall be made by the methods prescribed in Section 5.3.2.2.
2. Conduit penetrating the sheet steel shielded building may penetrate the sheet steel at any point.
3. Conduit penetrating the sheet steel shielded utility access tunnel may penetrate at any point.
4. Metal utility piping penetrations are treated the same as conduits.
5. Non-metal pipe penetrations through the building shield shall be

made through a wave guide.

6. Metal ducts, plenums, and similar type penetrations of the building shield shall be designed as wave guide type penetrations which maintain the shielding integrity of the shielded volume. If these ducts or plenums form completely shielded enclosures with the terminating equipment, no wave guide provisions are necessary (Sections 5.3.3.3, 5.3.4.3, 5.3.5.3, and 5.3.7.3).

2.3.9.1 Utility Piping - Type A

1. Within sheet steel shielded areas such as the control room or other group shielded areas, utility piping can be either metal or non-metal and has no NEMP requirement.
2. Outside sheet steel shielded areas within the building which is either unshielded or shielded by rebars, metal utility piping shall have the following requirements:
   a. Piping shall be electrically continuous.
   b. Piping shall be connected to the nearest internal ground ring.
   c. Metal piping sections which are bridged by a non-conducting pipe section shall have a No. 6 AWG copper bonding strap connected between metal pipe sections. Where bonding straps are not feasible, metal piping sections shall be connected at both extremities to the closest internal ground rings (Section 5.3.2.2).

2.3.9.2 Utility Piping - Type B

1. Within the sheet steel shielded building, utility piping can be either metal or non-metal.
2. Utility piping penetrations of the building shielding are covered under Penetrations.

2.3.10.1 Power Plant Building - Type A

The entire building shall be shielded with 11 gauge soli sheet steel fastened to the outside of the building. All seams and joi shall be

joined by continuous welding. All openings and penetrations in the overall metal skin shall be made in accordance with sections on openings and penetrations. This overall shield shall provide at least 40 dB of attenuation to a 10 kHz continuous magnetic field.

2.3.10.2 Power Plant Building - Type B

The entire building shall be shielded with 20 gauge solid sheet steel fastened to the inside of the building. All seams and joints shall be joined or fastened by spot welding. All openings and penetrations in the overall metal skin shall be made in accordance with the sections on openings and penetrations. This overall shield shall provide at least 40 dB of attenuation to a 10 kHz continuous magnetic field.

2.3.10.3 Power Plant Building - Type C

The entire building shall be shielded by means of reinforcing steel bars (rebars) welded to form electrically continuous loops in vertical planes throughout the length and width of the building. Thus, all vertical construction rebars in outer building walls shall be welded to form electrically continuous conductors and shall be welded at their upper extremities to roof rebars and at their lower extremities to the lowest courses of rebars to form electrically continuous loops.

In addition, the uppermost and lowermost courses of horizontal construction rebars shall be welded to form electrically continuous loops and all vertical rebar loops shall be welded at all points of intersection with these two horizontal loops. This overall shield shall provide at least 40 dB of attenuation to a continuous wave magnetic field in the frequency range between 10 and 100 kHz.

For example, this attenuation can be accomplished by a double course rebar continuous loop construction, using #14S (1.692 inch diameter) steel rebars on 14-inch centers. If double course rebar construction is chosen as the means of overall building shielding, the inner course of rebar shielding shall conform in construction to the outer course. Rebar

construction details and calculation procedures are given in Sections 5.3.4.2 and 5.3.4.3, respectively. Openings and penetrations in the overall rebar building shield shall be made in accordance with the sections on openings and penetrations.

2.3.10.4 Power Plant Building - Type D

The power plant building does not provide shielding for electrical equipment, wiring, or other electrical components inside.

3.0 PROTECTIVE RECOMMENDATIONS FOR FACILITIES ELECTRICAL SYSTEMS

3.1 Introduction

Recommendations for protecting the power building against electromagnetic pulse effects were given in Section 2.0. This section gives recommended protection measures for controlling electromagnetic pulse effects on site facilities electrical systems external to the power building. NEMP protection for the MSCB or DCCB is also covered. However, protective measures to attenuate the radio frequency radiation within these buildings are outside the bounds of NEMP protection.

The protective recommendations for the site facilities electrical systems are presented in shielding scheme format, as in Section 2.0. The recommendations are based upon the shielding required for susceptible items or subsystems exposed to the same environment (classified) as considered in Section 2.0.

3.2 Facilities Electrical System Protection Requirements

There are a number of facilities electrical system items or special construction features which may be required for NEMP protection, including

1. electrical raceways
2. electrical wiring
3. electrical equipment
4. equipment enclosures
5. grounding
6. openings
7. penetrations
8. utility piping

Protective recommendations for each of the above items are considered, wherever possible, in terms of the shielding schemes which may be used at the various site facilities.

3.3 Tabulated Guides to Recommended NEMP Protective Measures

As guides for determining applicable NEMP protective measures for

facilities, Tables 3.1 and 3.2 have been prepared. These tables list recommendations by types corresponding to the extent of NEMP protection provided by a particular shielding scheme. Under the type designation is given the subsection number which details the protective recommendations. These protective recommendation types, in conjunction with the tables, are related, wherever possible, to the protective recommendation types given in Section 2.0.

The recommendations chart, Table 3.1, applies to the MSCB only. Table 3.2 applies to unshielded facilities buildings and structures or to the interfaces between unshielded and shielded areas.

Details of the NEMP protective measures accompanying Tables 3.1 and 3.2 are presented in Sections 3.4 and 3.5, respectively.

3.4 MSCB Protective Recommendations

It should be recognized that the MSCB may have various degrees of shielding throughout the building dictated by factors which may be unrelated to NEMP protection. The electrical power system to these areas is the province of Section 3.5 and not the shielded areas themselves. This involves those areas which have no other shielding requirement except for NEMP and in which the electrical power system and its components are exposed to NEMP.

3.4.1.1 Electrical Raceways - Type B

1. Electrical raceways for power and power control wiring in the MSCB which are within local or group shielded areas having attenuation levels of 40 dB or greater to a 10 kHz continuous magnetic field shall follow Corps of Engineers requirements.
2. Electrical raceways for power and power control wiring in the MSCB which are outside of local or group shielded areas shall follow Type B electrical raceway requirements for the power building (Section 2.3.2.2).

TABLE 3.1

MSCB NEMP PROTECTIVE RECOMMENDATIONS

Environment →	(S)	(S)	(S)	(S)	(S)
Susceptible Item	Group	Local	Overall Rebar	Overall Sheet Steel Spot Weld	Overall Sheet Steel Cont. Weld
3.4.1 Electrical Raceways	Type B 3.4.1.1	Type B 3.4.1.1	Type C 3.4.1.2	Type D 3.4.1.3	Type D 3.4.1.3
3.4.2 Electrical Wiring	Type B 3.4.2.1	Type B 3.4.2.1	Type C 3.4.2.2	Type D 3.4.2.3	Type D 3.4.2.3
3.4.3 Electrical Equipment	Type C 3.4.3.1	Type C 3.4.3.1	Type D 3.4.3.2	Type E 3.4.3.3	Type E 3.4.3.3
3.4.4 Enclosures	Type C 3.4.4.1	Type C 3.4.4.1	Type D 3.4.4.2	Type E 3.4.4.3	Type E 3.4.4.3
3.4.5 Grounding	Type A 3.4.5.1	Type A 3.4.5.1	Type A 3.4.5.1	Type A 3.4.5.1	Type A 3.4.5.1
3.4.6 Openings	Type A 3.4.6.1	Type A 3.4.6.1	Type A 3.4.6.1	Type A 3.4.6.1	Type A 3.4.6.1
3.4.7 Penetrations	Type A 3.4.7.1	Type A 3.4.7.1	Type A 3.4.7.1	Type B 3.4.7.2	Type B 3.4.7.2
3.4.8 Utility Piping	Type A 3.4.8.1	Type A 3.4.8.1	Type A 3.4.8.1	Type B 3.4.8.2	Type B 3.4.8.2

3.4.1.2 Electrical Raceways - Type C

1. Electrical raceways for power and power control wiring in the MSCB which are within a rebar shielded area which provides at least 40 dB of attenuation to a continuous wave magnetic field in the frequency range of 10 to 100 kHz shall follow Type C electrical raceway requirements for the power building (Section 2.3.3.3).
2. Electrical raceways for power and power control wiring in the MSCB which are outside a rebar shielded area shall follow Type B electrical raceway requirements (Section 2.3.2.2).

3.4.1.3 Electrical Raceways - Type D

1. Electrical raceways for power and power control wiring in the MSCB which are within sheet steel shielded areas which provide attenuation levels of 40 dB or greater to a 10 kHz continuous magnetic field shall follow Type D electrical raceway requirements for the power building (Section 2.3.2.4).

3.4.2.1 Electrical Wiring - Type B

1. Electrical power and power control wiring in the MSCB which is located in locally or group shielded areas having an attenuation level of 40 dB or greater to a 10 kHz continuous magnetic field shall follow Corps of Engineers installation requirements.
2. Electrical power and power control wiring in the MSCB which is outside locally or group shielded areas shall follow Type B electrical wiring requirements for the power building (Section 2.3.3.2).

3.4.2.2 Electrical Wiring - Type C

1. Electrical power and power control wiring which is within a rebar shielded area which provides at least 40 dB of attenuation to a continuous wave magnetic field in the frequency range between 10 and 100 kHz shall follow Type C electrical wiring requirements for the power building (Section 2.3.3.3).

2. Electrical wiring which is outside rebar shielded areas shall follow Type B electrical wiring requirements of Section 3.4.2.1.

3.4.2.3 Electrical Wiring - Type D

1. Electrical power and power control wiring in MSCB which is shielded by sheet steel to attenuation levels of 40 dB or greater to a 10 kHz continuous magnetic field shall follow Type D electrical wiring requirements for the power building (Section 2.3.2.4).

3.4.3.1 Electrical Equipment - Type C

1. Electrical power and power control equipment in the MSCB which is located in group shielded areas or is locally shielded has no additional shielding requirement.
2. Electrical power and power control equipment in the MSCB which is outside group shielded areas and is not locally shielded shall follow Type C equipment requirements for the power building (Section 2.3.4.3).

3.4.3.2 Electrical Equipment - Type D

1. Electrical power and power control equipment in the MSCB which is located in rebar shielded areas shall follow Type D electrical equipment requirements for the power building (Section 2.3.4.4).

3.4.3.3 Electrical Equipment - Type E

1. Electrical power and power control equipment in the MSCB which is located in sheet steel shielded areas should follow Type E electrical equipment requirements for the power building (Section 2.3.4.5).

3.4.4.1 Enclosures - Type C

1. Enclosures for power wiring and equipment in the MSCB which are within or outside group or local shields shall follow Type C enclosure requirements for the power building (Section 2.3.5.3).

3.4.4.2 Enclosures - Type D

1. Enclosures for power wiring and equipment in the MSCB which are

located within rebar shielded areas shall follow Type D enclosure requirements for the power building (Section 2.3.5.4).

3.4.4.3 Enclosures - Type E

1. Enclosures for power wiring and equipment in the MSCB which are located in sheet steel shielded areas shall follow Type E enclosure requirements for the power building (Section 2.3.5.5).

3.4.5.1 Grounding - Type A

1. The MSCB grounding system shall follow Type A grounding requirements for the power building (Section 2.3.6.1). If the MSCB has an overall sheet steel shield, Type C grounding requirements shall be used.
2. Separate grounding systems for electronics or other specialized circuits are permitted provided these systems are interconnected with the MSCB grounding system by a suitable surge protector.

3.4.6.1 Openings - Type A

1. Openings in the MSCB shall follow Type A opening requirements for the power building (Section 2.3.7.1).

3.4.7.1 Penetrations - Type A

1. Conduit and utility penetrations of the MSCB and within the MSCB shall follow Type A penetration requirements for the power building (Section 2.3.8.1).

3.4.7.2 Penetrations - Type B

1. Where conduit and utility penetrations of the MSCB are through sheet steel, Type B penetration requirements for the power building (Section 2.3.8.2) shall apply.

3.4.8.1 Utility Piping - Type A

1. Utility piping in the MSCB which is located in areas not sheet steel shielded shall follow Type A utility piping requirements for the power building (Section 2.3.9.1).

3.4.8.2 Utility Piping - Type B

1. Utility piping in the MSCB which is located in sheet steel shielded

areas shall follow Type B utility piping requirements for the power building (Section 2.3.9.2).

3.5 <u>Protective Recommendations for Missile Farm Facilities (LS, LAA, and EDC), Missile Assembly Building (MAB), and Utility and Access Tunnel</u>

This section gives NEMP protective measures for the following facilities:

1. Missile Farm structures, consisting of launch stations (LS), launch area antennas (LAA), and an electrical distribution center (EDC). These facilities are hardened and require precise power.
2. The non-hardened Missile Assembly Building (MAB). Although non-hardened, this building requires precise power and its shielding is justified in order to prevent adverse NEMP effects upon it and upon other facilities using precise power.
3. The hardened utility and access tunnel.

For the LS, LAA, EDC, and MAB, two shielding schemes are practical:

1. Local shielding by individual enclosures.
2. Overall shielding using a continuously welded sheet steel enclosure.

For the utility and access tunnel, shielding being considered will consist of solid sheet steel with continuously welded seams applied throughout its length.

Details of the applicable NEMP protective measures are given in the following subsections.

3.5.1.1 Electrical Raceways - Type B

1. Electrical raceways for power and power control wiring which are within local shielded areas having attenuation levels of 40 dB or greater to a 10 kHz continuous magnetic field shall meet Corps of Engineers requirements.
2. Electrical raceways for power and power control wiring which are

TABLE 3.2

NEMP PROTECTIVE RECOMMENDATIONS FOR MISSILE FARM FACILITIES (LS, LAA, AND EDC), MISSILE ASSEMBLY BUILDING (MAB), AND UTILITY AND ACCESS TUNNEL

	LS, LAA, AND EDC		MAB		U & A TUNNEL
Environment →	(S)	(S)	(S)	(S)	(S)
Susceptible Item	Local	Overall*	Local	Overall*	Overall*
3.5.1 Electrical Raceways	Type B 3.5.1.1	Type D 3.5.1.2	Type B 3.5.1.1	Type D 3.5.1.2	Type D 3.5.1.2
3.5.2 Electrical Wiring	Type B 3.5.2.1	Type D 3.5.2.2	Type B 3.5.2.1	Type D 3.5.2.2	Type D 3.5.2.2
3.5.3 Electrical Equipment	Type C 3.5.3.1	Type E 3.5.3.2	Type C 3.5.3.1	Type E 3.5.3.2	Type E 3.5.3.2
3.5.4 Enclosures	Type C 3.5.4.1	Type E 3.5.4.2	Type C 3.5.4.1	Type E 3.5.4.2	Type E 3.5.4.2
3.5.5 Grounding	Type A 3.5.5.1	Type C 3.5.5.2	Type A 3.5.5.1	Type C 3.5.5.2	Type C 3.5.5.2
3.5.6 Openings	Type A 3.5.6.1	Type A 3.5.6.1	Type A 3.5.6.1	Type A 3.5.6.1	Type A 3.5.6.1
3.5.7 Penetrations	Type A 3.5.7.1	Type B 3.5.7.2	Type A 3.5.7.1	Type B 3.5.7.2	Type B 3.5.7.2
3.5.8 Utility Piping	Type A 3.5.8.1	Type B 3.5.8.2	Type A 3.5.8.1	Type B 3.5.8.2	Type B 3.5.8.2

* Overall signifies an overall sheet steel shield with continuous welds.

outside of, or interfaced with, local shielded areas shall follow Type B electrical raceway requirements for the power building (Section 2.3.2.2).

3.5.1.2 Electrical Raceways - Type D

1. Electrical raceways for power and power control wiring which are within overall shielded areas having attenuation levels of 40 dB or greater to a 10 kHz continuous magnetic field shall meet Corps of Engineers requirements.
2. Electrical raceways for power and power control wiring which penetrate overall shielded areas shall meet the requirements of Section 3.5.7.2.

3.5.2.1 Electrical Wiring - Type B

1. Electrical wiring within locally shielded areas having an attenuation level of 40 dB or greater to a 10 kHz continuous magnetic field shall follow Corps of Engineers installation requirements.
2. Electrical wiring outside of, or interfaced with, locally shielded areas shall follow Type B electrical wiring requirements for the power building (Section 2.3.2.2).

3.5.2.2 Electrical Wiring - Type D

1. Electrical wiring within overall shielded areas having an attenuation level of 40 dB or greater to a 10 kHz continuous magnetic field shall follow Type D electrical wiring requirements for the power building (Section 2.3.3.4).
2. Electrical wiring outside of, or interfaced with, overall shielded areas shall also follow Type D electrical wiring requirements for the power building (Section 2.3.3.4).

3.5.3.1 Electrical Equipment - Type C

1. Electrical equipment within locally shielded areas has no additional shielding requirement.
2. Electrical equipment outside locally shielded areas shall meet Type C shielding requirements (Section 2.3.4.3).

3.5.3.2 Electrical Equipment - Type E

1. Electrical equipment in overall sheet steel shielded areas should follow Type E electrical equipment requirements (Section 2.3.4.5).

3.5.4.1 Enclosures - Type C

1. Enclosures for power wiring and equipment constituting local shields shall follow Type C enclosure requirements (Section 2.3.5.3).

3.5.4.2 Enclosures - Type E

1. Enclosures for power wiring and equipment which are located within sheet steel shielded areas shall follow Type E enclosure requirements (Section 2.3.5.5).

3.5.5.1 Grounding - Type A

1. Grounding practices in locally shielded areas shall conform to Type A requirements (Section 2.3.6.1).
2. Separate grounding systems for specialized firing circuits, etc. are permitted provided such systems are interconnected with the building ground system by a suitable surge protector.

3.5.5.2 Grounding - Type C

1. Grounding practices in overall shielded areas shall conform to Type C requirements (Section 2.3.6.3).
2. Separate grounding systems for specialized firing circuits, etc. are permitted provided such systems are interconnected with the building grounding system by a suitable surge protector.

3.5.6.1 Openings - Type A

Regardless of the type of building or structure shielding provided, openings in shielding shall conform to the requirements of Section 2.3.7.1.

3.5.7.1 Penetrations - Type A

Conduit and utility penetrations of locally shielded areas shall conform to Type A penetrations requirements (Section 2.3.8.1).

3.5.7.2 Penetrations - Type B

Conduit and utility penetrations of overall shielded areas shall

conform to Type B penetrations requirements (Section 2.3.8.2).

3.5.8.1 Utility Piping - Type A

1. Utility piping outside locally shielded areas shall meet Type A utility piping requirements (Section 2.3.9.1).

3.5.8.2 Utility Piping - Type B

1. Utility piping within overall shielding shall meet Type B utility piping requirements (Section 2.3.9.2).

3.6 Protective Recommendations for Support Utilities Equipment Building

The five shielding schemes suggested for the power plant building (Section 2.2) are also being considered for the support utility equipment building.

Protective measures for the power building are, for the most part, applicable to the support utilities equipment building. Table 3.3 lists the reference sections that apply.

3.7 External Cabling between Facilities Buildings, Structures, or Areas

In this section the term "external cabling" shall be used to connote recommended electrical raceways as well as electrical wiring within such raceways. Requirements relating to each of these are stated in the following subsections.

3.7.1 Electrical Raceways between Facilities Buildings, Structures, or Areas

1. Conduits are the only approved raceways and shall be rigid steel or wrought iron, two inch electrical trade size or larger. Condulets shall not be used. Conduit joints shall be welded and threaded.
2. Conduits shall be continuous so that contained wiring is never directly exposed to NEMP fields.
3. Conduit runs which must be placed above ground level shall:
   a. be grounded by connection to counterpoise or ground rods at buildings (Section 5.3.2.2).

TABLE 3.3

NEMP PROTECTIVE RECOMMENDATIONS FOR SUPPORT UTILITIES EQUIPMENT BUILDING (Section 3.6)

Environment →	(S)	(S)	(S)	(S)	(S)
Susceptible Item	Group	Local	Overall Rebar	Overall Sheet Steel Spot Weld	Overall Sheet Steel Cont. Weld
Electrical Raceways	Type B 2.3.2.2	Type B 2.3.2.2	Type C 2.3.2.3	Type D 2.3.2.4	Type D 2.3.2.4
Electrical Wiring	Type B 2.3.3.2	Type B 2.3.3.2	Type C 2.3.3.3	Type D 2.3.3.4	Type D 2.3.3.4
Electrical Equipment	Type C 2.3.4.3	Type C 2.3.4.3	Type D 2.3.4.4	Type E 2.3.4.5	Type E 2.3.4.5
Enclosures	Type C 2.3.5.3	Type C 2.3.5.3	Type D 2.3.5.4	Type E 2.3.5.5	Type E 2.3.5.5
Grounding	Type A 2.3.6.1	Type A 2.3.6.1	Type B 2.3.6.2	Type C 2.3.6.3	Type C 2.3.6.3
Openings	Type A 2.3.7.1	Type A 2.3.7.1	Type A 2.3.7.1	Type A 2.3.7.1	Type A 2.3.7.1
Penetrations	Type A 2.3.8.1	Type A 2.3.8.1	Type A 2.3.8.1	Type B 2.3.8.2	Type B 2.3.8.2
Utility Piping	Type A 2.3.9.1	Type A 2.3.9.1	Type A 2.3.9.1	Type B 2.3.9.2	Type B 2.3.9.2
Support Utilities Equipment Building	Type D 2.3.10.4	Type D 2.3.10.4	Type C 2.3.10.3	Type B 2.3.10.2	Type A 2.3.10.1

b. be grounded by a 10 foot ground rod at the point of exit from the earth if this exit is more than 50 feet from the structure penetration.

c. be grounded by a direct connection to a 10 foot ground rod at intervals not exceeding 100 feet.

4. Conduit runs which are completely buried and less than 500 feet long need only be grounded at penetrations of other grounded structures. Conduit runs 500 feet or longer shall be grounded at one intermediate location for each 500 feet of conduit run.

5. Conduit penetrations at structures or manholes shall maintain the shielding integrity of the conduit.

6. Conduit runs to non-hardened loads shall meet the same NEMP requirements as conduit to hardened loads.

7. All conduit bends shall be radiused in accordance with standard requirements for the particular size conduit used.

3.7.2 Electrical Wiring between Facilities Buildings, Structures, or Areas

Electrical wiring must be shielded by shielding methods which provide at least 40 dB of attenuation to a 10 kHz continuous magnetic field. In the unshielded areas between buildings this required attenuation is provided by containment of the wiring in conduit (Section 3.7.1).

The following additional requirements for electrical wiring shall apply:

1. Power wiring shall have surge arresters installed on both hardened and non-hardened circuits. Installations shall be made at approved locations and by approved methods.
2. Separation between power and control wiring shall follow National Electrical Code or Corps of Engineers requirements.
3. Alarm and monitoring wiring between facilities buildings and a central monitoring location shall be for indication signals only. Such signal indicating circuits should be isolated from the primary alarm subsystem by relays or transformers.

3.8 Grounding and Surge Protection Recommendations for Certain Non-Hardened Facilities Buildings and Structures

Shielding is not considered economically feasible for certain non-hardened support buildings and structures supplied by commercial power because of their vulnerability to destruction by nearby nuclear detonation. Such buildings or structures include:

1. maintenance shops
2. mess hall
3. headquarters building
4. officer's quarters
5. barracks and unit administration building
6. assembly and training building
7. any above ground, non-hardened structures and the like, such as the helicopter facility, security and safety fencing, sentry stations, and site lighting standards.

There are, however, a number of protective and safety measures applicable to these buildings and structures to minimize the effects of overvoltage surges and to reduce the magnitude of NEMP induced currents entering the conduit subsystem routed to shielded buildings, structures, and areas. Recommendations are as follows:

1. Above ground structures and buildings shall be provided with a counterpoise and driven rod grounding system to which metal structural members shall be connected (Section 5.2.2.2).
2. If buildings or structures are to be equipped with lightning masts or air terminals, these shall be connected to the counterpoise ground system using at least two direct down leads of not less than No. 2 AWG copper (Section 5.2.3.1.2).
3. Hardware, metal utility piping and ducting, conduits, electrical equipment enclosure, and the like in non-hardened facilities buildings and structures shall be connected either to an internal

ground ring or directly to the grounding system, whichever is more direct. (Section 5.2.2.3).

4. Metal security and safety fencing shall be grounded at intervals not exceeding 500 feet by driven ground rods. In addition, ground rods shall be driven at each corner of a fenced-in area and connected to the fencing.
5. Ground rods shall be driven and connected to fencing on each side of all pedestrian and vehicle gates. These ground rods shall be connected by a buried counterpoise. Connections between counterpoise and security fencing shall be made by means of a No. 2 AWG or larger copper wire.
6. Pedestrian and vehicle gates shall be electrically connected to security fencing by means of flexible bonding straps having a conductivity at least as great as No. 1/0 AWG copper wire.
7. Site lighting standards, if constructed of metal and erected from the ground or at personnel access level, shall be grounded by connection to adjacent building steel, fencing, or to driven ground rods.

4.0 ELECTROMAGNETIC ENVIRONMENTAL EFFECTS ON ELECTRICAL POWER SYSTEMS

4.1 Introduction

The intent of this section is to present a brief summary of the electromagnetic pulse effects which are significant to a designer who has responsibility for a hardened electrical power system design. First it must be recognized that the electrical power system may be exposed to electromagnetic pulses which can enter the electrical system at many points and in many ways. The induced voltage response of each and every susceptible item in the system will determine the total system response. Therefore, of particular significance is the proper identification of those items which are susceptible and the degree to which they contribute to the response at various locations in the system where performance requirements must be maintained.

The following subsections will introduce the susceptibility of apparatus, components, and subsystems and how their individual susceptibilities relate to total system susceptibility and system performance requirements.

4.2 Electromagnetic Effects - Parametric Support Data

The "coupling" of electromagnetic fields into electrical power systems determines the induced voltages and currents at various points in the system. The calculations are very complex because of the many system configurations and geometries encountered. However, first step calculations have been made on some configurations to obtain realistic magnitudes of induced currents and voltages with which the designer must deal.

The specific configurations which will be discussed include:

1. Above ground transmission lines such as connections to commercial power and telephone services.
2. Conduit or cable loops where circulating currents may be induced by the magnetic field.
3. Long underground conductors which include cable and conduit runs, pipelines, and access tunnels.

4.2.1 Above Ground Transmission Line Currents

The calculation of above ground transmission line currents involves classified material and can be found in Reference 4.

4.2.2 Currents Induced in Conductor Loops

A closed loop of cable or conduit may interact with the magnetic field to produce a circulating current in the loop which depends upon the magnitude and time characteristics of the magnetic field and the loop area inductance and resistance. Because the inductance is a complicated function of loop dimensions and conductor size, it is not possible to give a simple relationship of peak current to loop area. A table of peak currents for several different conduit loops and conduit dimensions are given in Table 4.1 for a magnetic field of 100 A/m. The given values shown are for aluminum conduits or pipes. Currents induced in steel pipes or conduits will be somewhat less, so the tabulated values may be used safely. The designer can obtain peak currents for other magnetic field strengths by multiplying the given current values by $\frac{H}{100}$, where H is the new assumed magnetic field. Given also in the table are the voltages which would appear across a gap or break in the conduit loop. These voltages are shown to caution those responsible for system reliability and safety that discontinuities in conduit loops can be extremely dangerous. The values given in the table apply to conduit loops between metal cabinets and enclosures within buildings having dimensions as shown in Figure 4.1. For loop dimensions which do not vary more than a factor of 2 from those given, the tabulated value may be extrapolated.

4.2.3 Currents in Underground Conductors

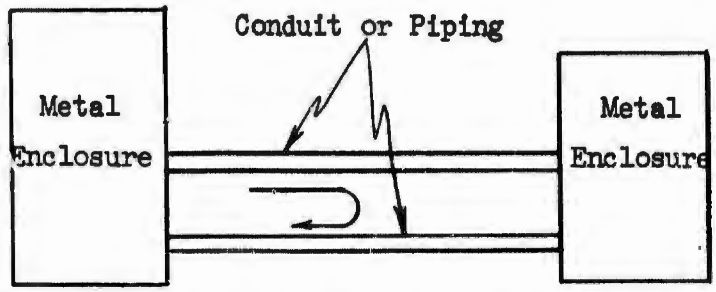
Another electromagnetic effect on the power system is the induced current on underground conductors which normally will be the conduit runs or pipes from buildings to outlying areas. The calculations and a detailed discussion of the phenomenon involved is given in Reference 1. The peak induced currents which the power system designer will use are given in

TABLE 4.1

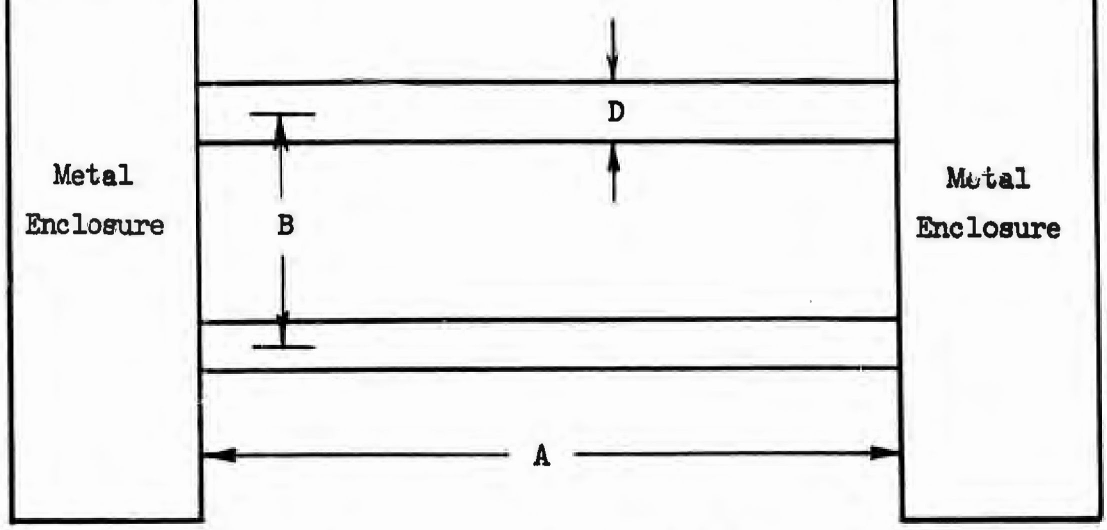
CURRENTS INDUCED IN CONDUCTOR LOOPS
at 100 amps/meter

A* (ft)	B* (ft)	D* (inches)	Aluminum I (amps)	Voltage (kV)
50	5	3	113	9.4
50	10	3	182	18.6
50	20	3	277	37.5
50	40	3	398	75.0
50	5	6	138	9.4
50	10	6	215	18.6
50	20	6	324	37.5
50	40	6	457	75.0
100	5	3	117	18.6
100	10	3	193	37.5
100	20	3	313	75.0
100	40	3	488	150.0
100	80	3	715	300.0
100	5	6	153	18.6
100	10	6	228	37.5
100	20	6	362	75.0
100	40	6	552	150.0
100	80	6	793	300.0
200	5	3	120	37.5
200	10	3	200	75.0
200	20	3	335	150.0
200	40	3	550	300.0
200	80	3	870	600.0
200	5	6	145	37.5
200	10	6	235	75.0
200	20	6	385	150.0
200	40	6	625	300.0
200	80	6	975	600.0

* For A, B, and D dimensions, see Figure 4.1.



A. Circulating Current Induced in Conduits and Piping between Metal Enclosures within Buildings



B. Geometry for Table 4.1

FIGURE 4.1 Currents Induced in Loops by a Magnetic Field

nomogram form in Figure 4.2 which relates peak current to magnetic field, ground conductivity, and conduit diameter. To use the nomogram, the designer needs to know the ground conductivity where the pipe or conduit is to be buried, the size conduit he intends to use, and the magnetic field to which the conduit will be exposed. As an example, assume the measured ground conductivity is 3.3×10^{-3} mho/meter and the intended conduit diameter is 2 inches. With a straightedge connect these two points and continue the line to the T axis. From this point on the T axis draw a line through the design magnetic field strength and read peak current. Assuming the design magnetic field was 500 amps/meter, the resulting peak current readout would be 50,000 amperes.

The analytical and experimental studies from which the nomograph was derived considered long conductor runs. In more recent experiments on shorter conduit runs, results indicate that for conduit runs of 5,000 feet and shorter the nomograph will yield conservative design data.

4.3 System Susceptibility

An electrical power system simply stated, is a network consisting of generating, distribution, and load equipment, each having its own complex control system, plus the necessary signaling, communication, and other accessory systems to make the power system function properly. All of these components and subsystems are directly or indirectly interconnected by electrical conductors and may be operating at widely different current and voltage levels. These electrical interconnections with their large number of electrical loops and long conductor runs are susceptible to EMP because of the induced currents and voltages which occur on the conductors. Then too, electrical equipment itself, most of which functions by means of an induction principle, has a varying degree of susceptibility.

To precisely determine the susceptibility of an electrical power system to an EM pulse, the complete system would have to be in place. Analysis would have to proceed by an experimental approach with the system properly

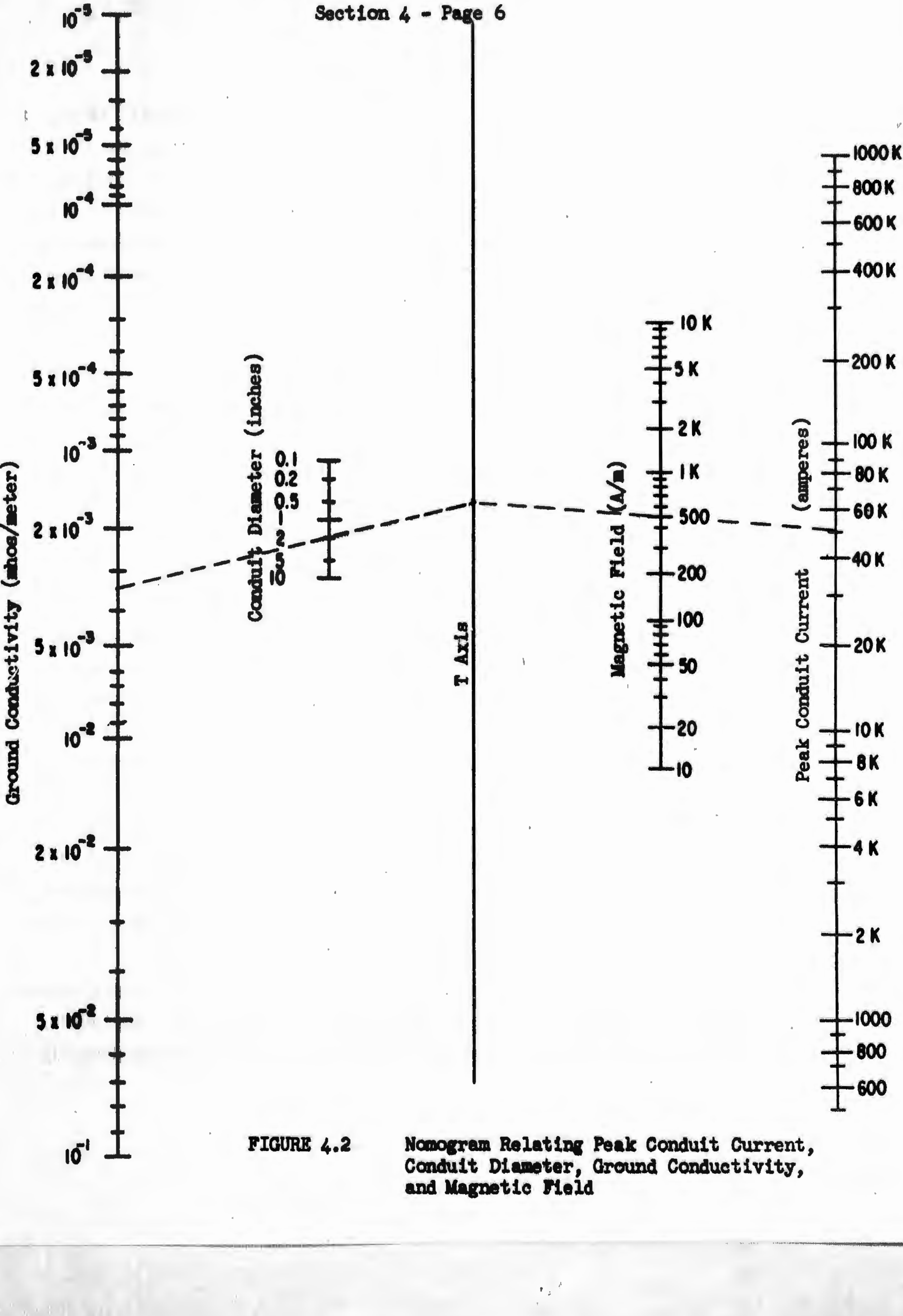


FIGURE 4.2 Nomogram Relating Peak Conduit Current, Conduit Diameter, Ground Conductivity, and Magnetic Field

instrumented and variations in field orientation taken into account to obtain maximum response values. While this approach is not impossible, it is impractical because it requires that a complete design be formulated before the application of protection and shielding techniques could take place. Therefore, in the development of these protective recommendations a different analytical and experimental approach to system susceptibility was deemed necessary. The procedure used is outlined as follows:

1. The individual equipment and component responses with orientations to the applied field resulting in maximum susceptibility were determined. Equipment and components were electrically disconnected from sources and loads to obtain "worst case" results.
2. The magnitudes of these induced voltages were related from all parts of a feeder back to the bus. The total feeder overvoltage contribution to the bus overvoltage was found to be the rms summation of the individual contributions. For any load with a multiplicity of equipment and components, the maximum induced voltage of the most susceptible item was taken to represent the total load overvoltage contribution.
3. The total primary bus overvoltage was determined by rms summing of all feeder contributions.
4. The primary bus overvoltage was then compared with performance requirements.
5. If system performance requirements were not met, protective measures were established to reduce induced overvoltages to acceptable levels. These are given in Sections 2.0 and 3.0 for an assumed typical system.

The above approach has the advantage of permitting design changes in parts of the electrical system without requiring a reanalysis of the whole system. This design flexibility comes at the price of creating an electrical power system protection scheme which will be conservative.

Electrical power and distribution systems have certain basic design features and associated apparatus which are common. For example, an electrical power system would in all probability contain electrical apparatus such as generators, motors, transformers, regulators, circuit breakers, and components such as motor control contactors, relays of all types, instruments and meters of all types, etc., as well as the circuits to which these various equipments are connected. Such electrical components and apparatus [illegible] be used as a basis for experimental and analytical study of susceptibility and response.

4.3.1 Power Distribution Circuits

A realistic beginning to a susceptibility analysis is to first consider the wiring. Consider a 13,800 or 4160 volt, 3 ø unenclosed primary bus system connecting generators together as shown in Figure 4.3.

The line-to-line voltage V developed across phases B and C in such a circuit is a function of the phase loop dimensions, the rate of change of flux through the loop and the circuit parameters. A realistic condition would be one in which a minimum of four generators are connected to a no-load bus system having surge suppression capacitors connected line-to-ground at each generator. (Reference 2, page 5-6). The analysis of such a condition results in line-to-line overvoltages as shown in Table 4.2.

TABLE 4.2

PRIMARY BUS OVERVOLTAGES FOR VARIOUS MAGNETIC FIELD STRENGTHS
(given in times rated peak line-to-line voltage)

Unenclosed Conductors	PER UNIT BUS OVERVOLTAGE FOR 13800 VOLT SYSTEM		
	100 amperes/meter	500 amperes/meter	1000 amperes/meter
100 ft. bus	0.024	0.12	0.24
200 ft. bus	0.033	0.16	0.33
300 ft. bus	0.042	0.21	0.42
1000 ft. bus	0.076	0.38	0.76

Table 4.2 (cont.)

Unenclosed Conductors	PER UNIT BUS OVERVOLTAGE FOR 4160 VOLT SYSTEM 100 amperes/meter	500 amperes/meter	1000 amperes/meter
100 ft. bus	0.079	0.39	0.79
200 ft. bus	0.112	0.56	1.12
300 ft. bus	0.137	0.68	1.37
1000 ft. bus	0.240	1.2	2.40

Since the per unit bus overvoltage values given in Table 4.2 all exceed a 2% bus performance requirement (0.02 times rated peak line-to-line voltage on a per unit basis), it is obvious that EMP shielding is necessary for buses on either voltage system. It should also be noted that as the system voltage decreases, the per unit overvoltage increases proportionately. It should also be recognized that unenclosed buses are potentially hazardous to power plant personnel; they are vulnerable to external mechanical damage and cannot contain a fire started by a flashover. Therefore, bus enclosures designed to provide EMP shielding as well as mechanical protection are necessary. The required degree of attenuation for bus runs of 100 feet or more, exposed to H-field environments of 30 amperes per meter or more, can be obtained from the nomograms, Figures 4.4 and 4.5. Uses of these nomograms are detailed in the following design examples:

1. Assume that the ambient magnetic field in the power building is 300 amperes per meter and that the power bus is 200 feet long, operating at 13800 volts. To determine the shielding attenuation that must be provided by a bus enclosure to meet a 2% performance requirement, proceed as follows:

   On the nomogram for a 13800 volt bus, Figure 4.4, align the 300 amperes per meter assumed magnetic field value on the left stem with the 200 foot bus run mark on the right stem. Read the required bus shielding attenuation (approximately 14 dB) on the

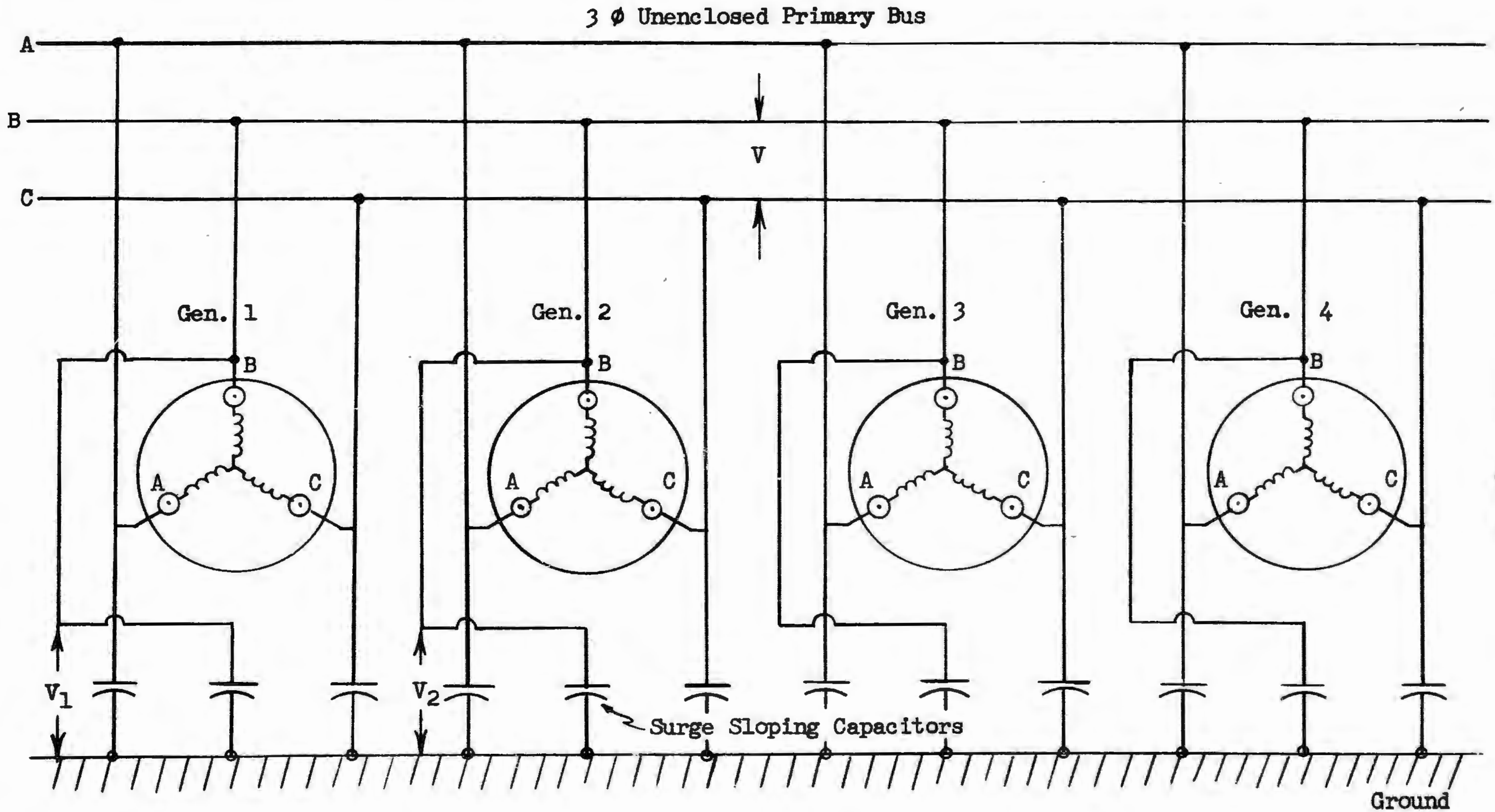


FIGURE 4.3 Primary Bus of System Having No Magnetic Shielding Connecting Four Generators

7

right side of the intermediate stem. The per unit system overvoltage that would appear on an unshielded 13,800 volt bus can be found at the corresponding position on the left side of the intermediate stem. In this instance it would be 0.1 of the rated peak line-to-line system voltage, or about 1950 volts.

2. Now, suppose it is known that a particular bus duct for a 4160 volt power system can provide a maximum shielding attenuation of 30 dB and the bus run is again 200 feet long. It is desired to determine the maximum ambient field that could appear in the power building, yet allow this bus to meet its 2% performance requirement.

   On the nomogram for a 4160 volt bus, Figure 4.5, align the 30 dB attenuation value on the right side of the intermediate stem with the 200 foot bus length mark on the right stem and read approximately 580 amperes per meter on the left stem as the maximum allowable ambient field in which this bus could meet the 2% overvoltage requirement.

Another important consideration which must continually be kept in mind is the problem of personnel safety and overvoltage to equipment from induced voltages. In the circuit shown in Figure 4.3, consider the voltages V_1 and V_2 which are developed line-to-ground by the occurrence of an EM pulse. For a 50 foot conductor run having an enclosed area of 500 square feet, the total voltage $V_1 + V_2 = V'$ for a 100 amp/meter magnetic field rising to crest value in one microsecond would be

$$V' = \mu_o A \frac{dH}{dt} = 4\pi \times 10^{-7} \times \frac{500}{(3.28)^2} \times \frac{100}{10^{-6}} = 5850 \text{ volts}$$

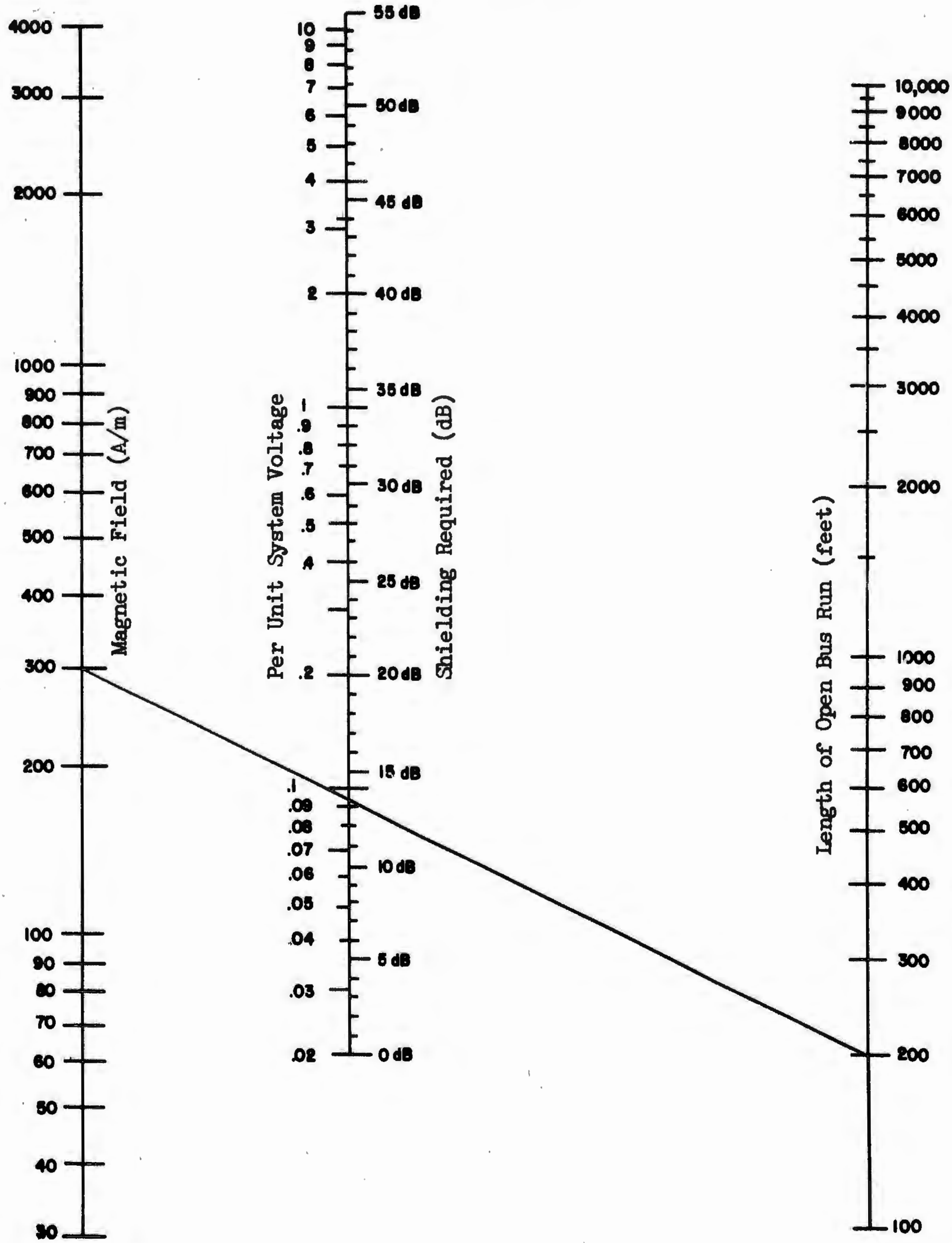


FIGURE 4.4 13,800 Volt System

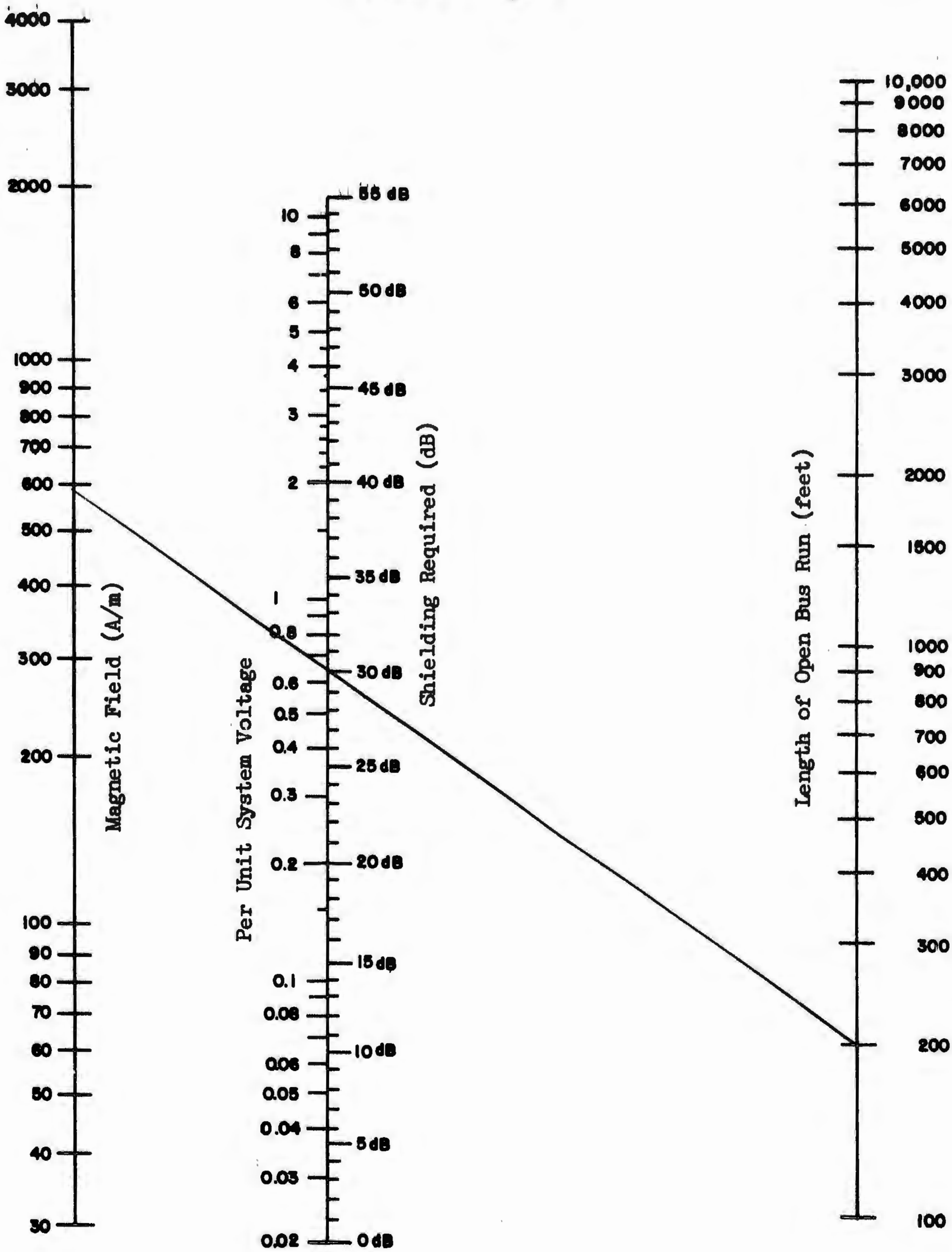


FIGURE 4.5 4160 Volt System

At 1000 amps/meter, the voltage would be 58,500 volts. These voltages could be extremely dangerous to personnel and may cause equipment malfunction and damage.

The voltages V_1 and V_2 can exist in any unshielded electrical circuit and, therefore, the use of conduit or enclosures for all electrical wiring is necessary to minimize those voltages for safety and circuit performance requirements.

4.3.2 Apparatus, Components, and Subsystem Susceptibility

All electrical apparatus is susceptible to the effects of electromagnetic pulse energy in varying degrees. In an attempt to identify and evaluate those equipments which are susceptible, a series of analytical and experimental studies were made. (Reference 2, page 5-1). The electrical apparatus evaluated included motors, generators, transformers, voltage regulators, and relays of varying sizes. Evaluations were also made on energized systems. "Worst case" H-field orientation was used in all tests.

The following series of figures, 4.6 through 4.10, gives the magnitude of the voltage induced in various kinds of electrical apparatus when that apparatus is exposed to simulated NEMP magnetic fields. The data given are for isolated unenergized equipment. This also represents a "worst case" condition. For some apparatus the analytical values are given along with the experimental results. In developing the criteria the experimentally obtained induced voltage values were used for all cases except where a design curve was established to account for possible effects such as differences in equipment size, ratings, or unusual design features not foreseen.

4.4 System Response and Propagation Characteristics

The overvoltages which appear at the terminals of interconnected electrical equipment due to exposure to a varying magnetic field can propagate throughout the electrical system. The magnitude of these overvoltages at any given location in the system depends on many variables such as the EM pulse wave shape, the electrical system impedance network, the location of

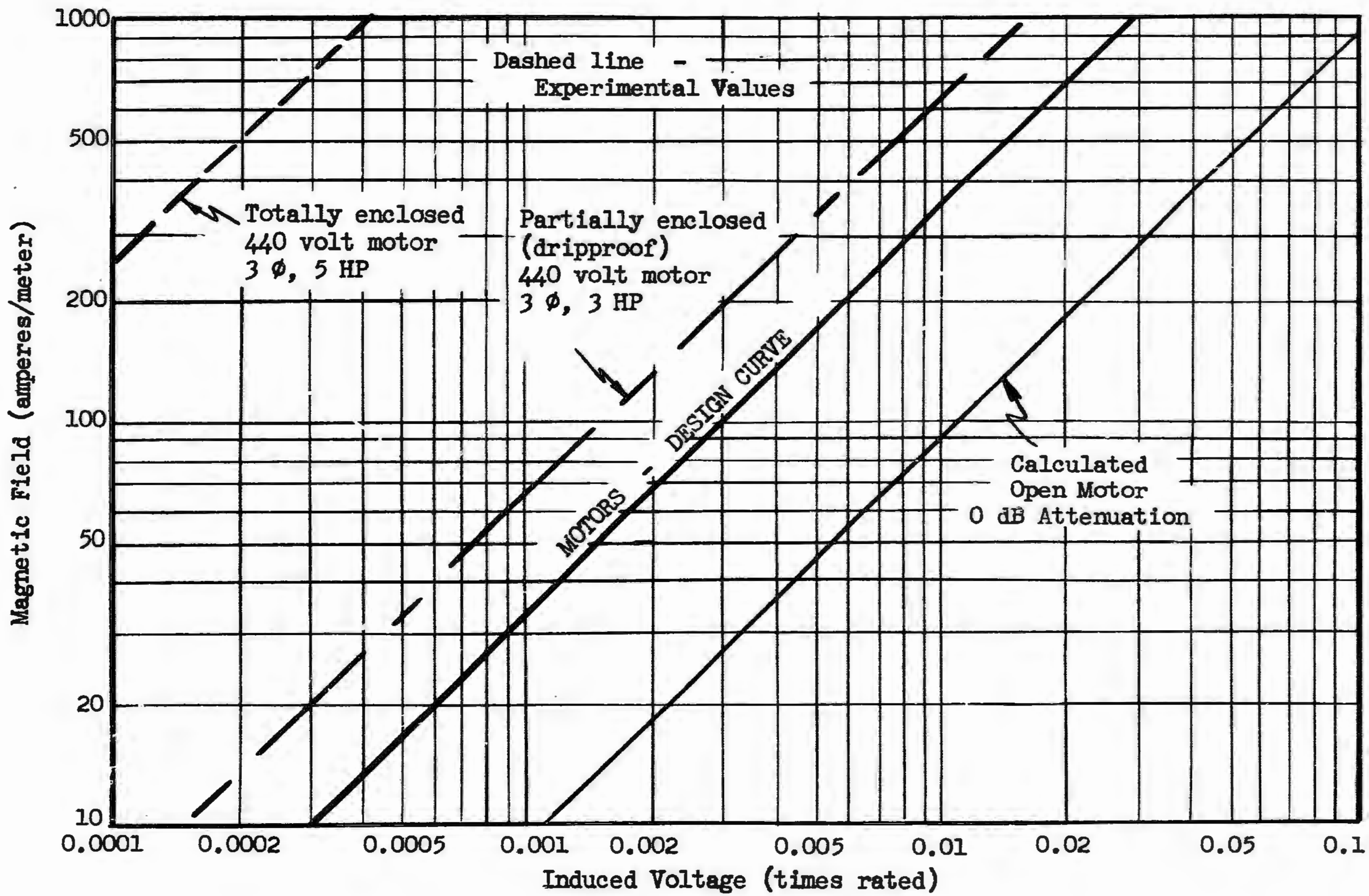


FIGURE 4.6 Induction Motor Induced Voltage versus Magnetic Field

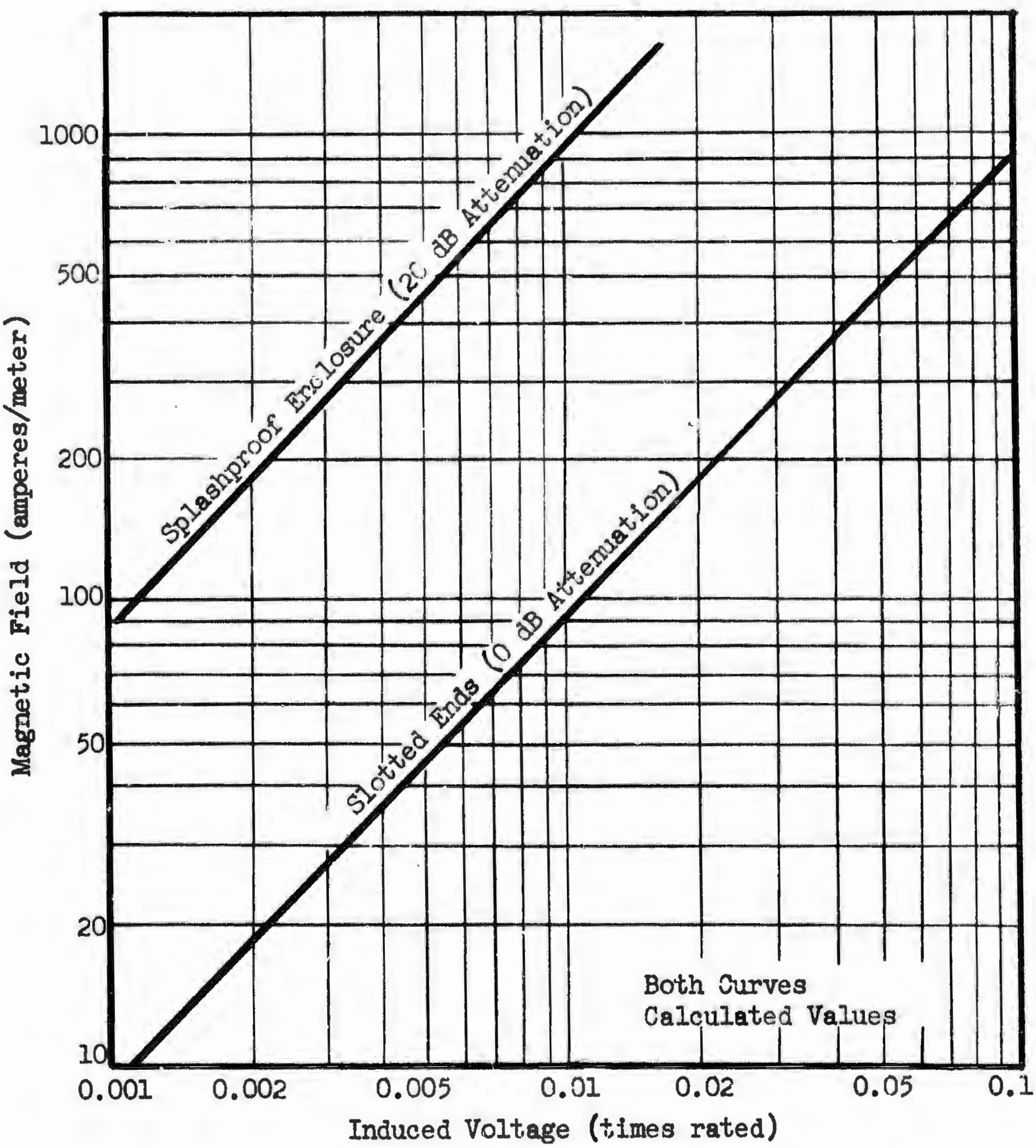


FIGURE 4.7 Generator Induced Voltage versus Magnetic Field

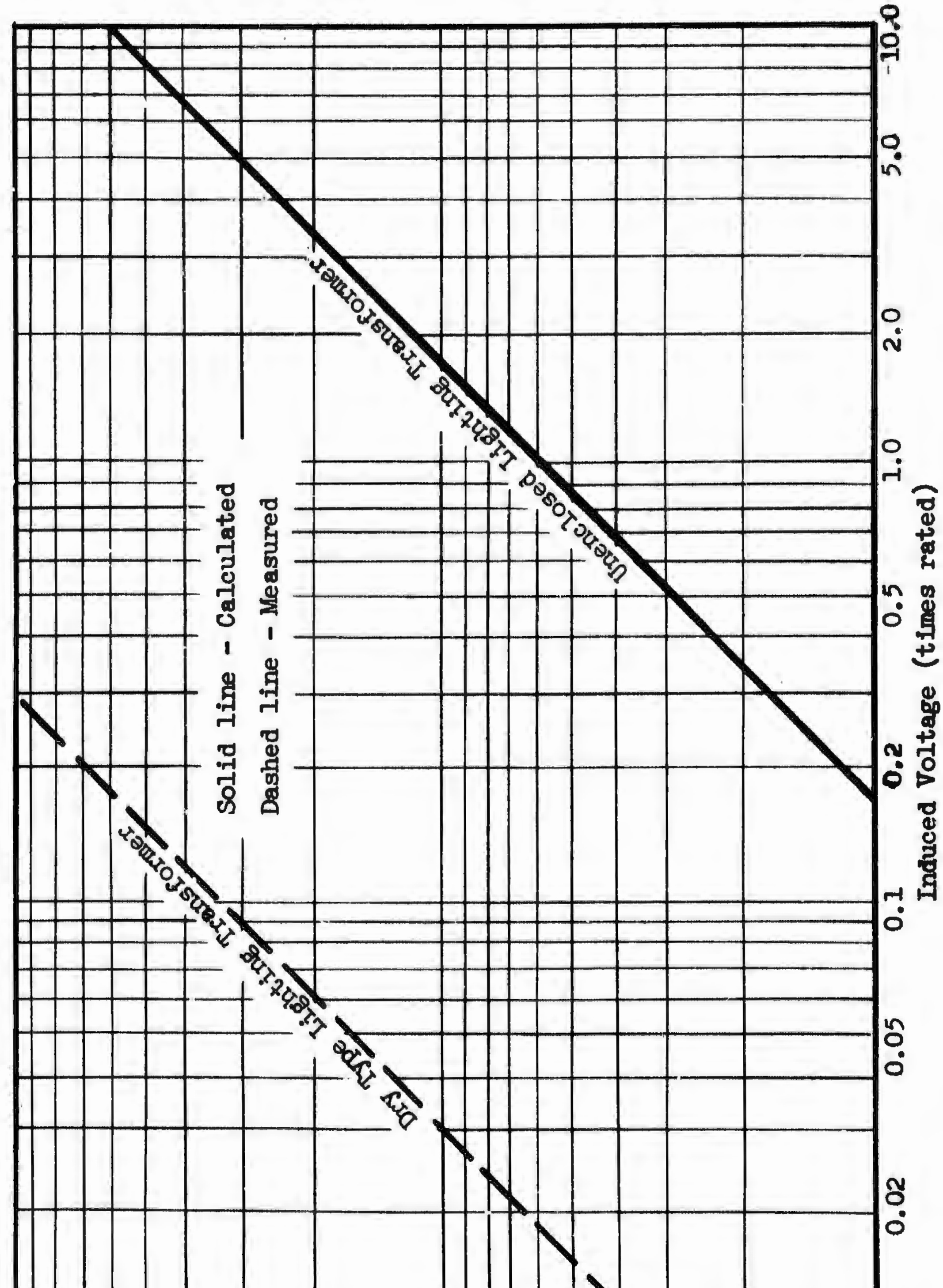


FIGURE 4.8 Dry-type Lighting Transformer Induced Voltage versus Magnetic Field

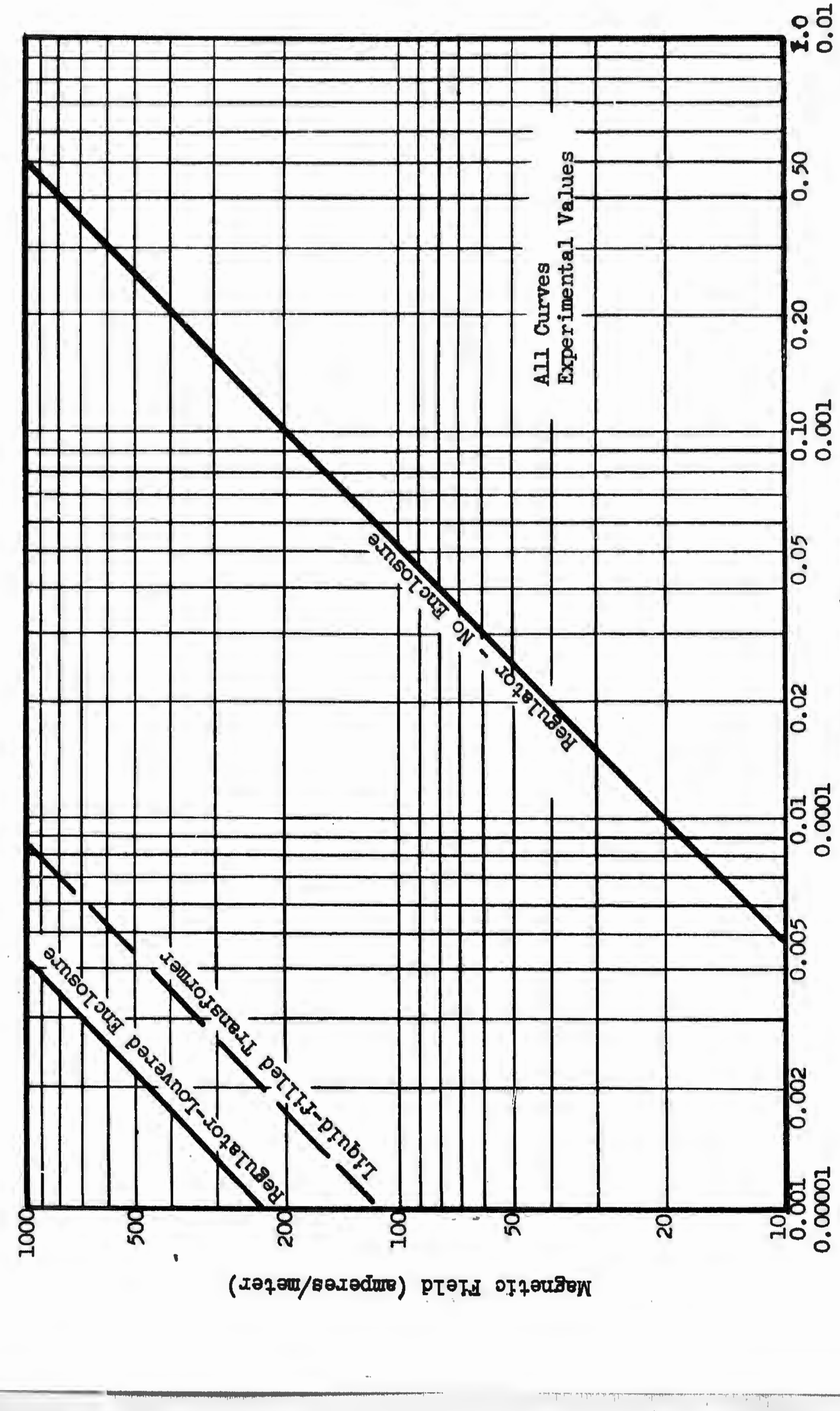


FIGURE 4.9 Liquid-Filled Distribution Transformer and Dry-type Induction Voltage Regulator (lower abscissa for transformers - upper abscissa for regulators)

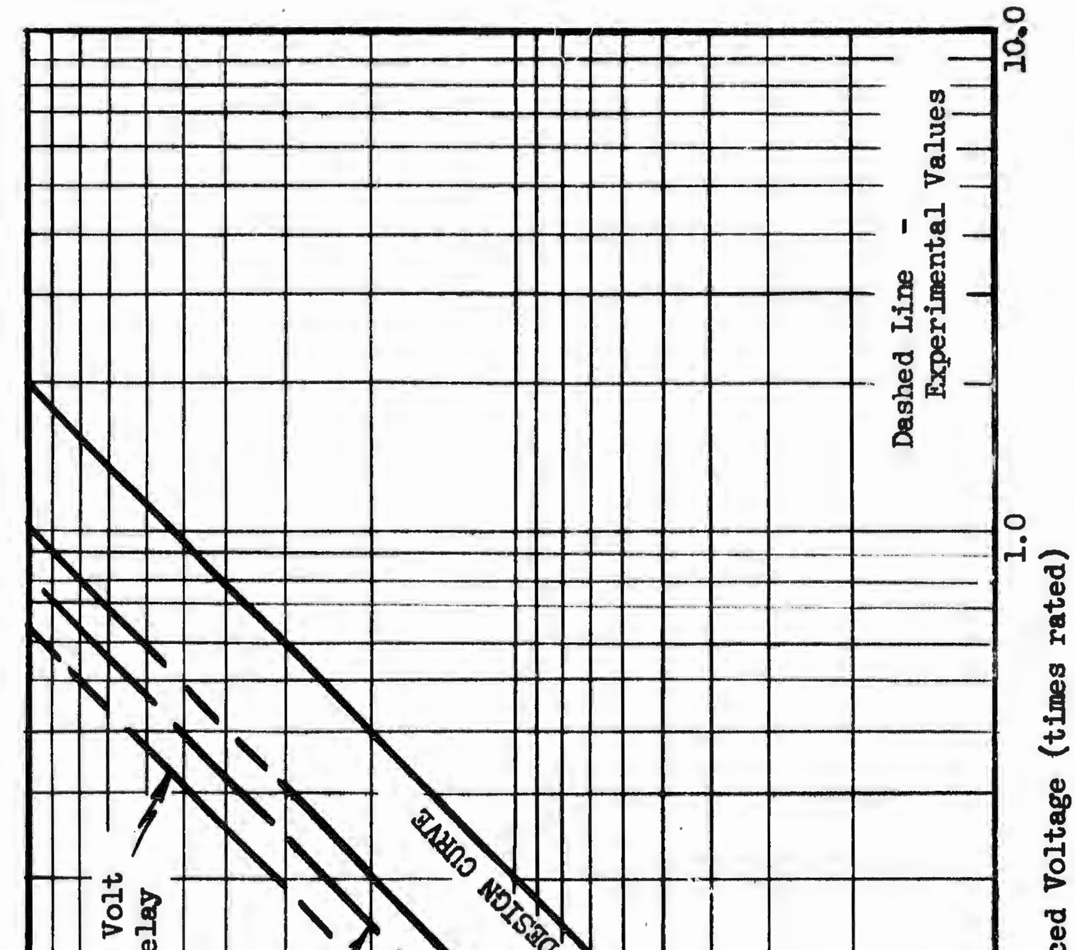
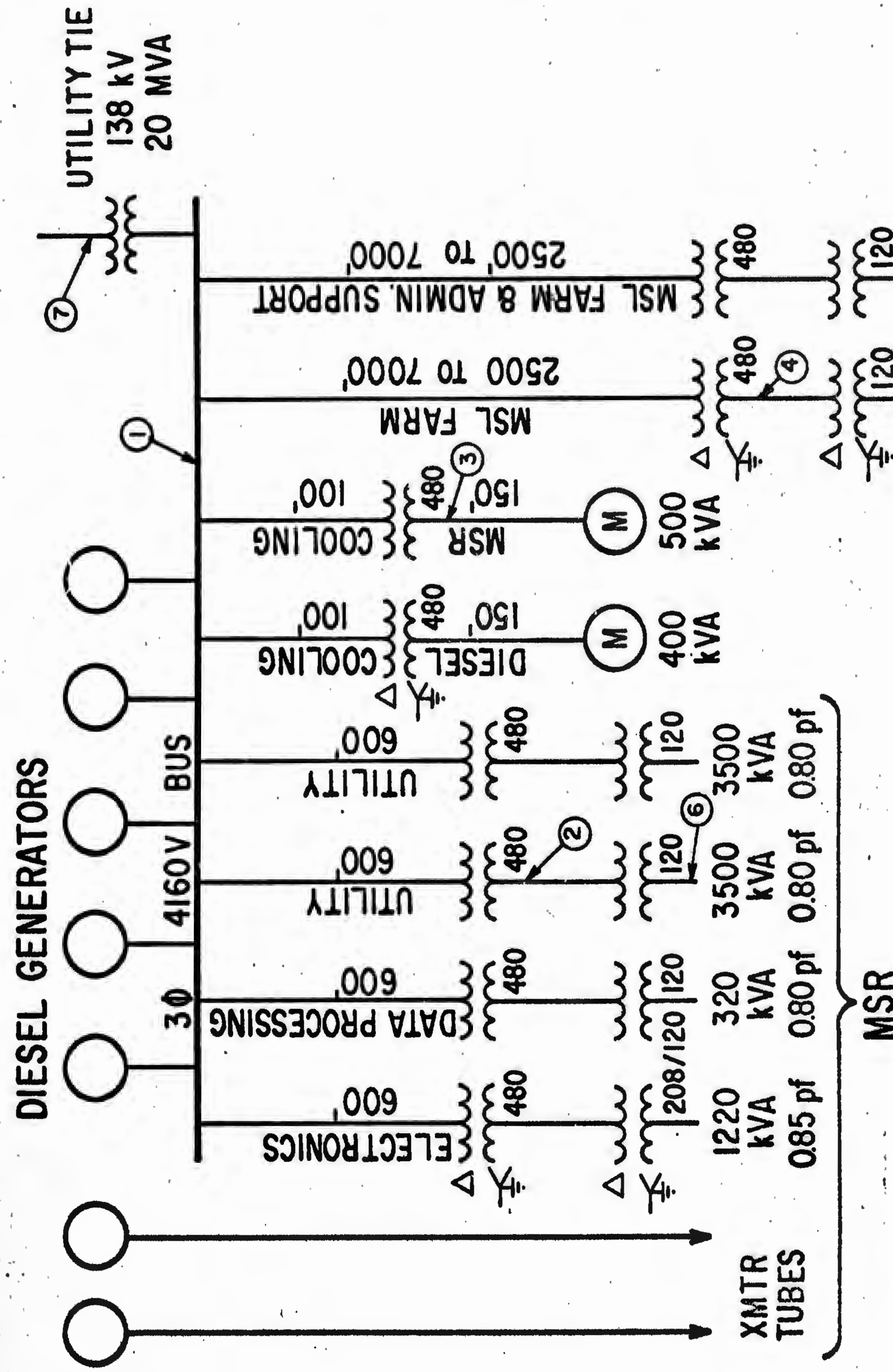


FIGURE 4.10   Control Relay Induced Voltage versus Magnetic Field

overvoltage injection and the circuit impedance at the point of injection. An overvoltage pulse which may not be detrimental to equipment or the system at the point of injection may cause equipment damage or electrical system malfunction in some other part of the system.

Analysis of transient behavior of a particular electrical system must necessarily be performed on the system in question. When no such system exists, analysis can proceed on the basis of a typical system such as shown in Figure 4.11. The transient behavior of this typical system was studied by means of a Transient Network Analyzer (Reference 2, page 4-8) which injected either single phase line-to-line or line-to-ground voltage pulses at various locations and measured the resultant transient voltages throughout the electrical system. This simulates the appearance and propagation of H-field produced voltage pulses from motors, relays, transformers, and similar induction-type equipment. Also it simulates the voltage pulses produced on conductors within conduit exposed to an H-field environment as well as transients produced by switching and lightning. For the case of induction-type equipment the induced voltage response of one phase, either line-to-line or line-to-ground, is usually higher than the other two phases because of the orientation of the equipment in respect to the H-field direction. This induced voltage will propagate back to the generator bus in a manner shown in Table 4.3, which gives the response characteristics of the typical system shown in Figure 4.11 for an applied step-function wave. The voltages applied at the various load locations and measured on the generator bus are given in per unit values. For the case of induced voltages on conductors within conduit, either voltage between conductors or the same voltage to ground on all conductors is possible, as will be explained later. Table 4.3 gives the designer the means to calculate 1) the primary bus response due to a transient voltage injected single phase into the system either line-to-line or line-to-ground and 2) the response which propagates from the generator bus along all other feeders due to an



TYPICAL MSR POWER SYSTEM

FIGURE 4.11

TABLE 4.3

TRANSIENT BEHAVIOR FOR TYPICAL ELECTRICAL SYSTEM

All voltages given in per unit values of peak rated voltage

Transient Input Location for Line-to-Neutral or Line-to-Line Injection (1.0 per unit voltage applied)	Transient Voltage on Generator Bus: Line-to-Neutral A-G	B-G	C-G	Line-to-Line A-B	B-C	C-A	Time to Crest µs **
(1) 4160 Volt Bus	1.80	1.0	1.80	$\frac{1.40}{\sqrt{3}}$	$\frac{1.30}{\sqrt{3}}$	0	-
(2) 480 V - 350 kVA	0.01*	0.04	0.04	$\frac{0.04}{\sqrt{3}}$	$\frac{0.09}{\sqrt{3}}$	$\frac{0.04}{\sqrt{3}}$	80
(3) 480 V - 500 kVA (motor load)	0	0.01	0.01	$\frac{0.01}{\sqrt{3}}$	$\frac{0.03}{\sqrt{3}}$	$\frac{0.01}{\sqrt{3}}$	100
(4) 480 V - 500 kVA	0	0.01	0.01	$\frac{0.01}{\sqrt{3}}$	$\frac{0.02}{\sqrt{3}}$	$\frac{0.01}{\sqrt{3}}$	80
(5) 120 V - 500 kVA	0.01*	0.01*	0.01*	0	$\frac{0.01^*}{\sqrt{3}}$	$\frac{0.01^*}{\sqrt{3}}$	80
(6) 120 V - 3500 kVA	0.01	0.02	0.02	$\frac{0.02}{\sqrt{3}}$	$\frac{0.045}{\sqrt{3}}$	$\frac{0.02}{\sqrt{3}}$	80
(7) 138 kV - Utility (20 MVA)	0	0.53	0.53	$\frac{0.53}{\sqrt{3}}$	$\frac{0.98}{\sqrt{3}}$	$\frac{0.53}{\sqrt{3}}$	60

* Measurement was less than 0.01. Use 0.01 for calculations.

** For all voltages except input impulse.

Note: Transient input locations refer to the circled numbers shown in Figure 4.11.

overvoltage originating on a given feeder. Methods and procedures used to calculate the responses are given in Section 4.5, Design Examples.

To clarify the terms used in Table 4.3 consider the MSL Farm feeder shown in Figure 4.11 showing voltage injection points (4) and (5). Note that location (5) in Table 4.3 indicates that a 1.0 per unit line-to-neutral voltage on the 120 volt circuit results in a $\frac{0.01}{\sqrt{3}}$ per unit L-L bus voltage. In terms of voltage this indicates that a 170 volt peak transient (1.0 per unit L-N) on the 120 volt circuit will result in a $\frac{0.01}{\sqrt{3}} \times 4160 \times \sqrt{2} = 34$ volt line-to-line peak transient on the 4160 volt bus. This is illustrated in A of Figure 4.12. From location (4) in the table the response at the generator bus can be calculated due to a transient on this 480 volt circuit. A 1.0 per unit line-to-line peak overvoltage ($480 \times \sqrt{2} = 680$ volts, for example) on the 480 volt circuit results in a $\frac{0.02}{\sqrt{3}}$ per unit line-to-line bus voltage. Therefore, a 68 volt peak transient would appear on the generator bus due to a 680 volt line-to-line peak transient on the 480 volt circuit, as shown pictorially in B of Figure 4.12. In a similar manner the designer can determine the overvoltage at the primary bus due to a single phase peak overvoltage from any part of any feeder circuit.

The designer may also need to know the response which would appear at a given feeder or load circuit when the generator is subjected to an overvoltage from another feeder. Transient Network Analyzer measurements have indicated that for this condition the generator bus overvoltage will propagate essentially unattenuated along other feeders. The examples in the section following will help to clarify the calculation of these transient effects.

As was mentioned earlier, the maximum induced voltages on phase conductors in conduit runs exposed to an H-field environment can occur either as a voltage between conductors or as the same voltage on all conductors. The induced voltages resulting from flux leakages at bends and couplings

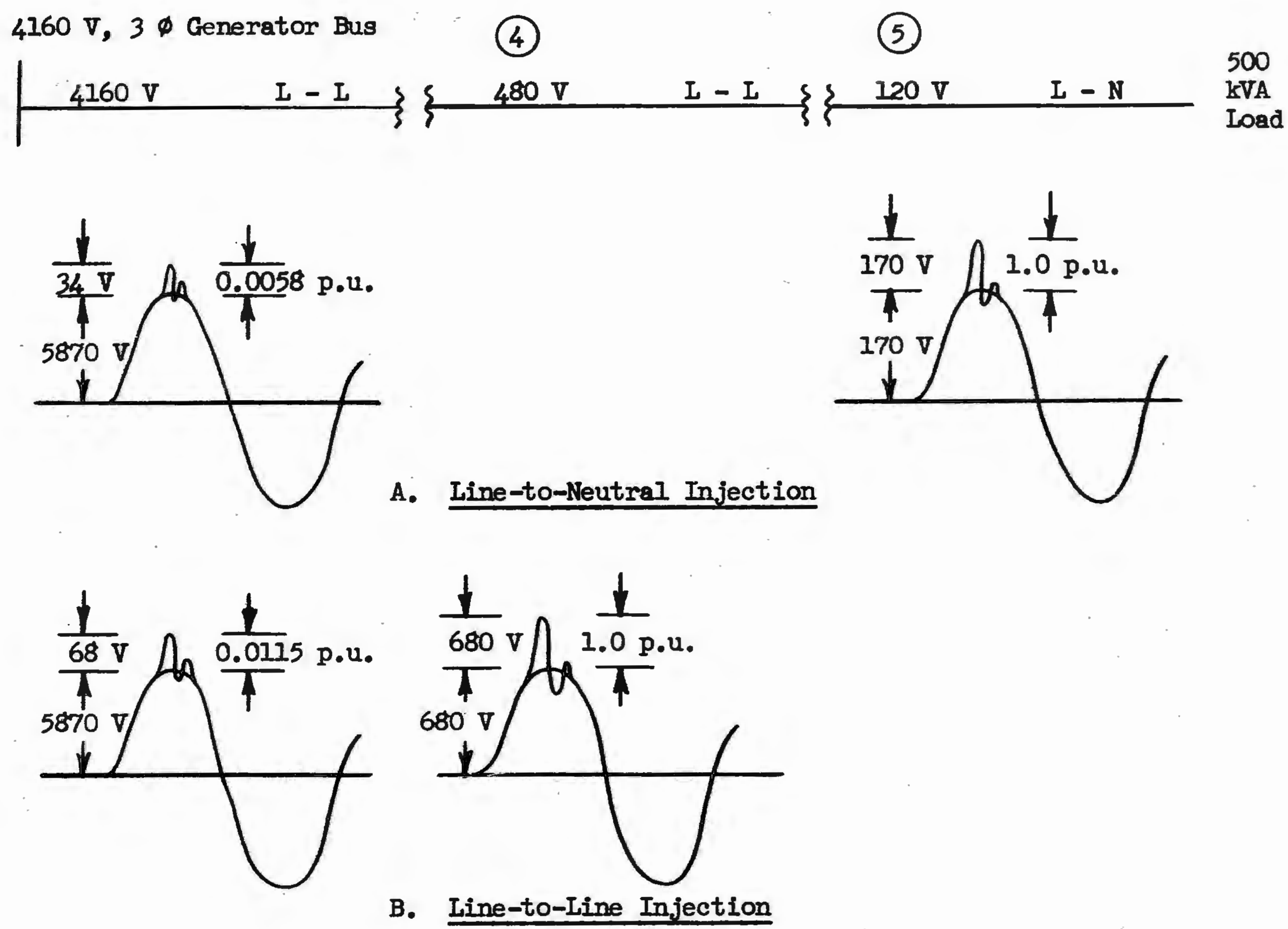


FIGURE 4.12 Transient Response of MSL Farm Feeder Circuit

results in a voltage to ground as well as between conductors and Table 4.3 does apply. The induced voltage resulting from the IR drop in the conduit length results in essentially simultaneous and equal voltages between each phase conductor and ground. For simultaneous voltage injection on all three phase conductors, experimental studies (Reference 2, page 4-18) have shown that both the resulting line-to-line and line-to-ground generator bus overvoltages are virtually zero when the transient pulse propagates through a wye-delta transformation as indicated in Figure 4.11. If, however, the transformation is through a grounded Y-grounded Y transformer, the line-to-line induced voltage at the generator bus can be calculated by using Table 4.3, considering the induced voltage as a line-to-ground injection. This calculated per cent voltage at the bus will propagate along all other feeders at this same per cent magnitude. This approach will lead to worst case results.

In the power system there also are conduit runs containing three phase power cable connected directly to the generator bus such as a long conduit run to an outlying area. The induced voltage on these cables due to an H-field exposure will appear line-to-line and line-to-ground directly on the bus. Line-to-ground induced voltages on these conductors due to the IR drop (length effect) of the conduit will again appear essentially simultaneously between all three phase conductors and ground and will be of equal magnitude. Experiments have shown that again these induced line-to-ground voltages cause no generator bus line-to-line overvoltage. These line-to-ground induced voltages may, however, propagate along other feeders and may affect sensitive circuits. Therefore, the following general rule applies: for a three phase simultaneous and equal line-to-ground voltage injection at the generator bus virtually no <u>line-to-line</u> transient voltage will appear on any load circuit if the injected voltage propagates through delta-wye or wye-delta transformations. If the transformation is grounded wye to grounded wye, then the line-to-ground induced voltage propagates unattenuated

to any and all load circuits. No line-to-line transient voltages will be experienced on any three phase circuits. The 120 volt circuit, however, will experience the total induced line-to-ground voltage.

The following section will help clarify some of the points just discussed.

4.5 Design Examples

First it must be recognized that in an electrical power system exposed to EMP there are:

1. Equipments which, by nature of their physical make-up, are more susceptible than other electrical equipment.
2. Equipments which are critical as to their electrical location in the power system and, therefore, may have more stringent transient voltage requirements.
3. Certain aspects of the system which must be analyzed from a sub-system point of view in addition to an individual component or equipment approach.

ITEM 1. Voltages will be induced in all inductive apparatus such as motors, generators, transformers, regulators, electromagnetic actuators, relays, etc. when they are exposed to changing magnetic fields. Apparatus which is enclosed in metal enclosures will be less susceptible, have lower response, than unenclosed apparatus. For instance, a totally enclosed motor is less susceptible than a dripproof motor which in turn is less susceptible than an open motor. (See Figure 4.6)

ITEM 2. The performance specifications of the power system may not only apply to the primary bus but on some load circuits as well. Induced voltages from equipment and conduit on these critical load circuits must be held within specifications, possibly by additional shielding.

ITEM 3. This relates to the wiring and interconnection between equipment, long conduit runs between facilities and outlying areas.

Recognizing these basic facts, the determination of the protection requirements necessary to meet certain given power system performance specifications can then proceed. First, the EM pulse field specification for the site must be given. If this is assumed to be 500 amperes/meter, the procedure would then be to determine protection requirements and techniques on a component, equipment, and subsystem basis. If the system performance requirements cannot be met on this basis, then room or building shielding will have to be considered. In dealing with components and equipment, two things must be considered:

1. The EMP protection necessary to prevent damage and malfunction of equipment due to induced voltage in the equipment itself.
2. The transient overvoltages transmitted to other parts of the system due to the overvoltage induced in the equipment itself.

To determine the overvoltages developed in equipment and components, the designer should refer to Section 4.3.2, Figures 4.6 through 4.10, and read out the overvoltage induced by exposure to a magnetic field. For a 500 amperes/meter magnetic field, these overvoltages are listed in Table 4.4.

TABLE 4.4

TRANSIENT OVERVOLTAGES INDUCED IN ELECTRICAL EQUIPMENT DUE TO A MAGNETIC FIELD OF 500 A/m

Equipment	Induced Voltage (Times Peak Rated)
Motors - Design Curve	0.015
Generators - Splashproof	0.0055
Transformers - Dry type	0.15
Transformers - Liquid-filled	0.000045
Regulators - Louvered	0.0022
Relays - Design Curve	1.0

The per unit overvoltages induced by the magnetic field are next

compared in Table 4.5 to the per unit dielectric test voltage levels which this equipment must withstand without being damaged.

TABLE 4.5

COMPARISON OF INDUCED TRANSIENT OVERVOLTAGES IN EQUIPMENT AT 500 AMPERES/METER TO THE EQUIPMENT DIELECTRIC TEST VOLTAGE LEVELS

Equipment	Induced Overvoltage (p.u. of peak rated voltage)	Equipment Dielectric Test Voltage Levels (p.u. of peak rated line-to-ground voltage)
Motors rated 480 V, 3 ø	0.015	7.0
Motors rated 120 V, 1 ø	0.015	10.4
Generators rated 13,800 V, 3 ø	0.007	3.6
Transformers - 120 V Secondary, 1 ø	0.000045	83.4
Transformers - 480 V Secondary, 3 ø	0.000045	36.2
Relays - 120 V, 1 ø	1.00	10.4
Relays - 480 V, 3 ø	1.00	7.0
Regulators - 480 V, 3 ø	0.002	14.5

As can be noted, the transient overvoltages induced in the kinds of electrical equipment listed are extremely small in comparison to what the equipment will withstand and will not cause damage to this equipment. Additional shielding is, therefore, not required from a damage point of view.

Wiring was discussed in Section 4.3.1 where it was determined that all open wire must be placed in conduit or other shielded enclosure. Conduit, however, exposed to an electromagnetic pulse is also susceptible by virtue of the induced current which flows along its length. This current causes a voltage to be induced between conductors within the conduit as well as between conductors and conduit. This induced conductor voltage is a function of the induced conduit current magnitude, the H-field environment surrounding the conduit, the length of the conduit runs, the number and type of conduit bends, the number of threaded joints and the type of wire within the

conduits. The voltage magnitudes induced on conductors within conduits as affected by these parameters is shown in Figures 4.13, 4.14, and 4.15. These curves apply for two inch rigid steel conduit or larger. To use these curves for other conduit materials, multiply the values found on the curves by the factors given in Table 4.6.

TABLE 4.6

MULTIPLYING FACTORS FOR USE WITH FIGURES 4.13, 4.14, AND 4.15 RELATING TO USAGE OF VARIOUS ELECTRICAL CONDUITS

	FACTORS FOR				
	Figure 4.13	Figure 4.14		Figure 4.15	
Conduit Type	C-G	C-G	C-C	C-G	C-C
1" rigid steel	2.0	1.0	1.0	1.0	1.0
Wrought Iron	3.0	1.0	1.0	1.0	1.0
Electrical Metallic Tubing (steel)	30.0	1.0	1.0	1.0	1.0
Aluminum	30.0	1.0	1.0	1.0	1.0
2" rigid steel with 1 foot flexible carbon steel bellows	*	*	*	*	*
Aluminum or Steel Armor Cable	300	65	50	65	50
Sealtite Flexible Conduit	4000	1250	1000	1250	1000

The asterisk (*) in Table 4.6 relating to the use of bellows in a conduit run denotes that a simple multiplying factor is not possible. For the long time response the bellows also allows a conductor-to-conduit voltage to develop simultaneously and equally on all three phase conductors but at a different time than that resulting from the conduit length effect. In a conduit run employing one bellows, the induced conductor-to-conduit voltage due to the bellows is lower than that due to the conduit length when the conduit length exceeds 1600 feet. For the two bellow case the same situation occurs when the conduit length exceeds 3200 feet. Therefore, when

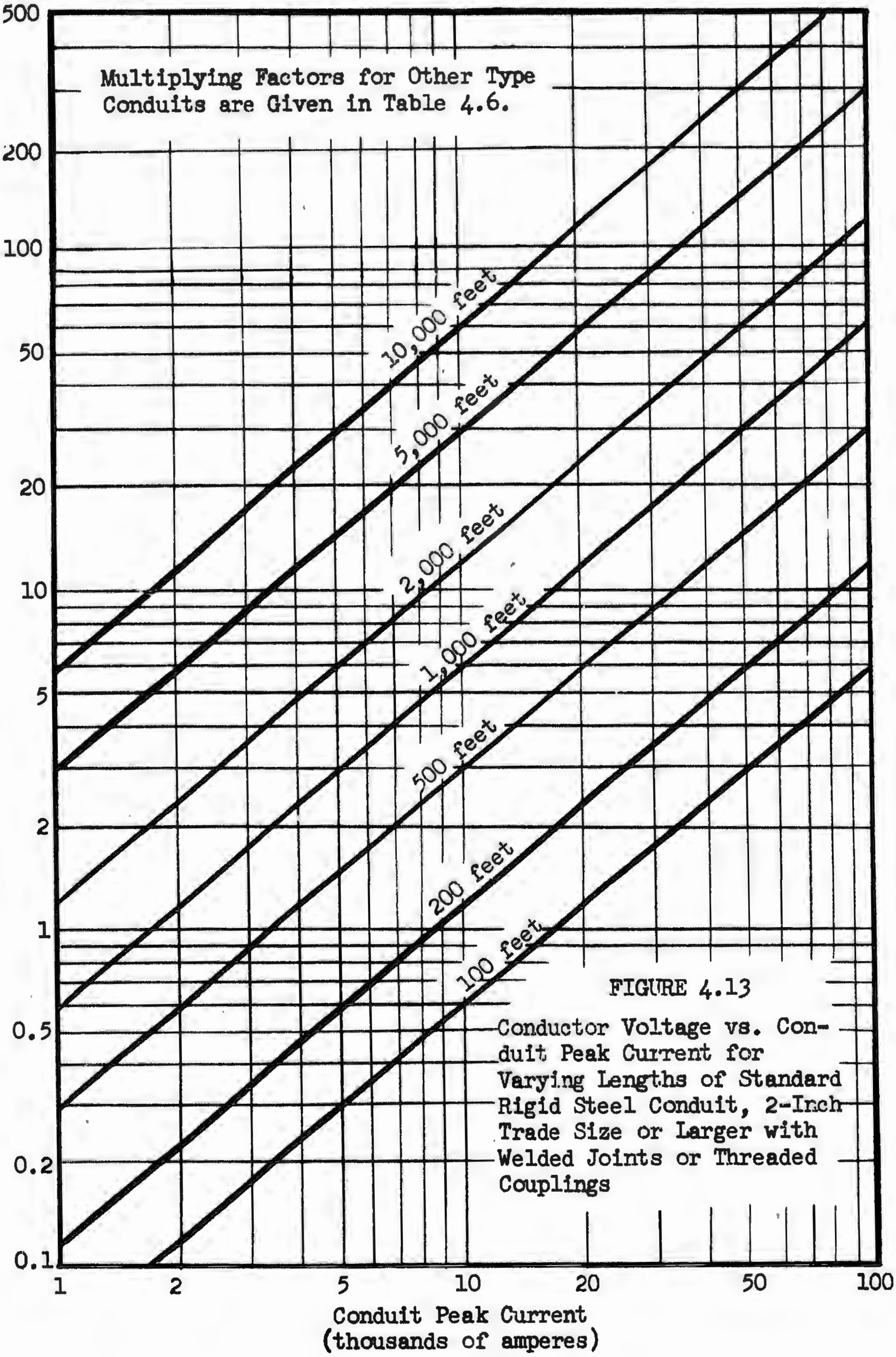


FIGURE 4.13

Conductor Voltage vs. Conduit Peak Current for Varying Lengths of Standard Rigid Steel Conduit, 2-Inch Trade Size or Larger with Welded Joints or Threaded Couplings

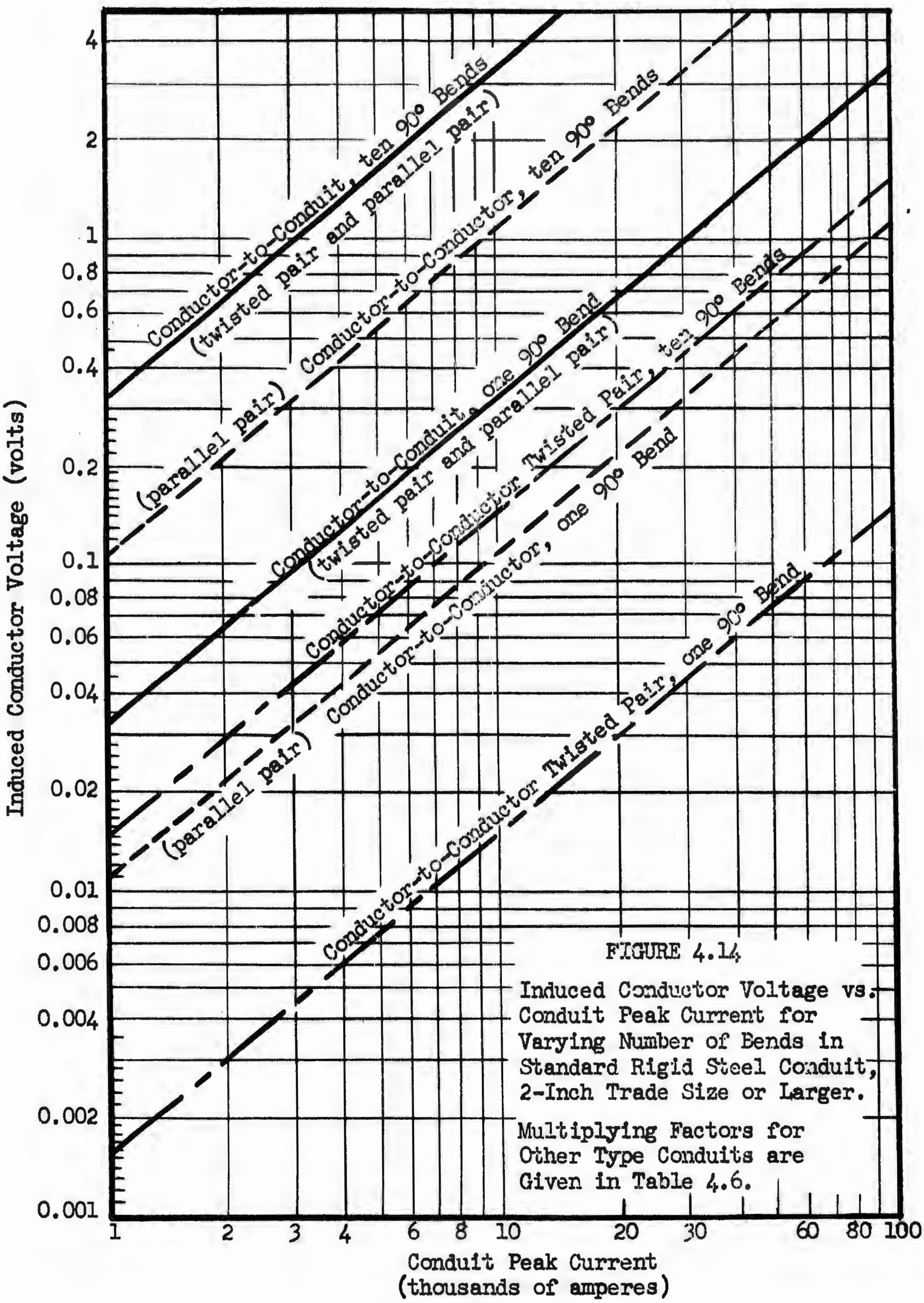


FIGURE 4.14

Induced Conductor Voltage vs. Conduit Peak Current for Varying Number of Bends in Standard Rigid Steel Conduit, 2-Inch Trade Size or Larger.

Multiplying Factors for Other Type Conduits are Given in Table 4.6.

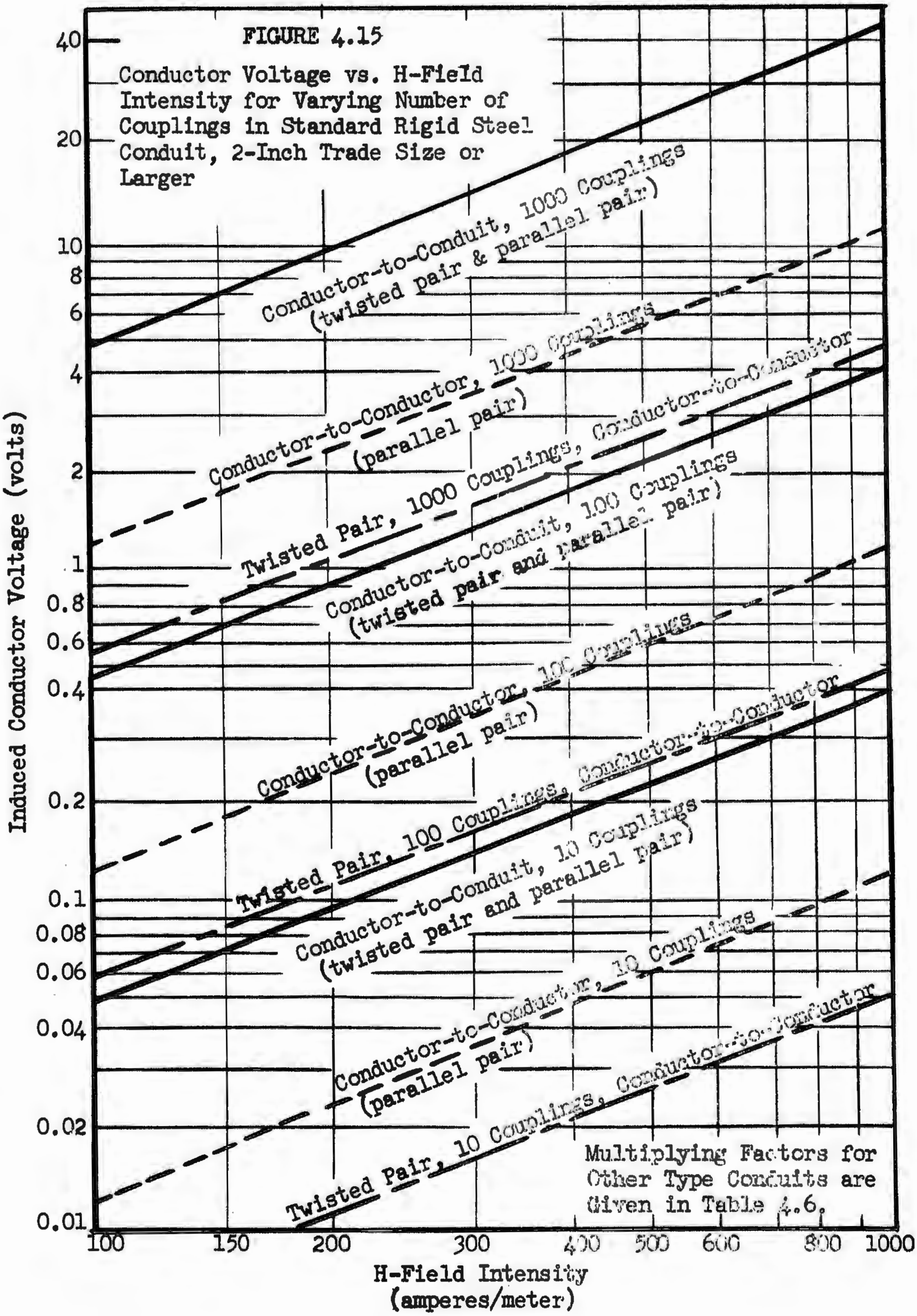


FIGURE 4.15
Conductor Voltage vs. H-Field Intensity for Varying Number of Couplings in Standard Rigid Steel Conduit, 2-Inch Trade Size or Larger
Conductor-to-Conduit, 1000 Couplings (twisted pair & parallel pair)
Conductor-to-Conductor, 1000 Couplings (parallel pair)
Twisted Pair, 1000 Couplings, Conductor-to-Conductor
Conductor-to-Conduit, 100 Couplings (twisted pair and parallel pair)
Conductor-to-Conductor, 100 Couplings (parallel pair)
Twisted Pair, 100 Couplings, Conductor-to-Conductor
Conductor-to-Conduit, 10 Couplings (twisted pair and parallel pair)
Conductor-to-Conductor, 10 Couplings (parallel pair)
Twisted Pair, 10 Couplings, Conductor-to-Conductor
Multiplying Factors for Other Type Conduits are Given in Table 4.6.
Induced Conductor Voltage (volts)
40
20
10
8
6
4
2
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
100
150
200
300
400
500
600
800
1000
H-Field Intensity (amperes/meter)

determining the induced conductor-to-conduit voltage for conduit runs with bellows, determine the conduit length effect induced voltage from Figure 4.13 and the bellows effect induced voltage from Figure 4.16 and use whichever is higher, but not both.

For the short time response, bellows also allow a conductor-to-ground and conductor-to-conductor induced voltage to develop at the same time as the response from conduit bends and couplings. The induced voltages due to bellows are given in Figure 4.17 and must be added to the short time response induced voltages given in Figures 4.14 and 4.15 for conduit.

4.5.1 Response Calculations Demonstrating Procedure

The method of analysis can best be shown by considering a typical simplified situation such as shown in Figure 4.18. Assume a power building which must provide power for an outlying area 500 feet away at 480 volts. The ground conductivity was measured to be 3.3×10^{-3} mhos/meter. The current which will flow on the conduit for a magnetic field of 500 amperes/meter can be obtained from the nomogram, Figure 4.2, Section 4.2.3. For the given case, 50,000 amperes would flow on the conduit. The induced voltage on the conductors within the conduit can be obtained from Figures 4.13, 4.14, and 4.15. For a 2-inch rigid steel conduit the induced conductor-to-conductor and conductor-to-conduit voltages are given in Table 4.7.

TABLE 4.7

INDUCED VOLTAGES ON CONDUCTORS IN RIGID STEEL CONDUIT

(H = 500 A/m; Conduit Current = 50,000 amp; Conduit Length = 500 feet)
(Ground Conductivity 3.3×10^{-3} mho/meter)

	Peak Induced Voltage		
Condition	Figure 4.13 50,000 amps	Figure 4.14 50,000 amps	Figure 4.15 500 amps/meter
Conduit Length (500')	CG 15 Volts		
Number of * Conduit Bends		CG 4.95 Volts CC 0.22 Volts	
Number of ** Conduit Couplings			CG 1.20 Volts CC 0.14 Volts

Continued . . . .

CG - Conductor-to-ground
CC - Conductor-to-conductor
* - 3 conduit bends, twisted pair wire assumed
** - 50 couplings, twisted pair wire assumed

The induced voltages given in this table will appear on the 480 volt circuit but not necessarily at the same time. Note that the induced voltage due to conduit length is developed as a "long-time" effect appearing equally from each phase conductor-to-ground (line-to-ground), while the induced voltages due to conduit bends and couplings are developed as "short-time" effects appearing unequally on each phase conductor-to-ground. (Reference 2, page 5-12) Conductor-to-conduit (line-to-ground) voltages shown in Table 4.7 are maximum voltages that would appear on one of the three phase conductors to ground. Conductor-to-conductor (line-to-line) voltages shown in the table are the maximum voltages that would appear between any two phase conductors due to the unequal line-to-ground effects.

Assume as an example that this particular 480 volt circuit feeds a number of motor leads each with associated starting and control equipment. As shown in Section 4.3.2, motors, solenoids, and transformers are susceptible to electromagnetic fields. The maximum single phase induced voltage resulting from a given EMP field exposure can be obtained from Figure 4.6 for motors, Figure 4.10 for solenoids, and Figure 4.9 for transformers. These induced voltages are given in Table 4.8.

TABLE 4.8

INDUCED VOLTAGE RESPONSE FROM MOTORS, SOLENOIDS, AND TRANSFORMERS SUBJECTED TO A 500 A/m FIELD

Item	Induced Voltage Response (times rated peak voltage)
Motors - Figure 4.6	0.015
Solenoid - Figure 4.10	1.0 (only this one is significant)
Transformers - Figure 4.9	0.000045

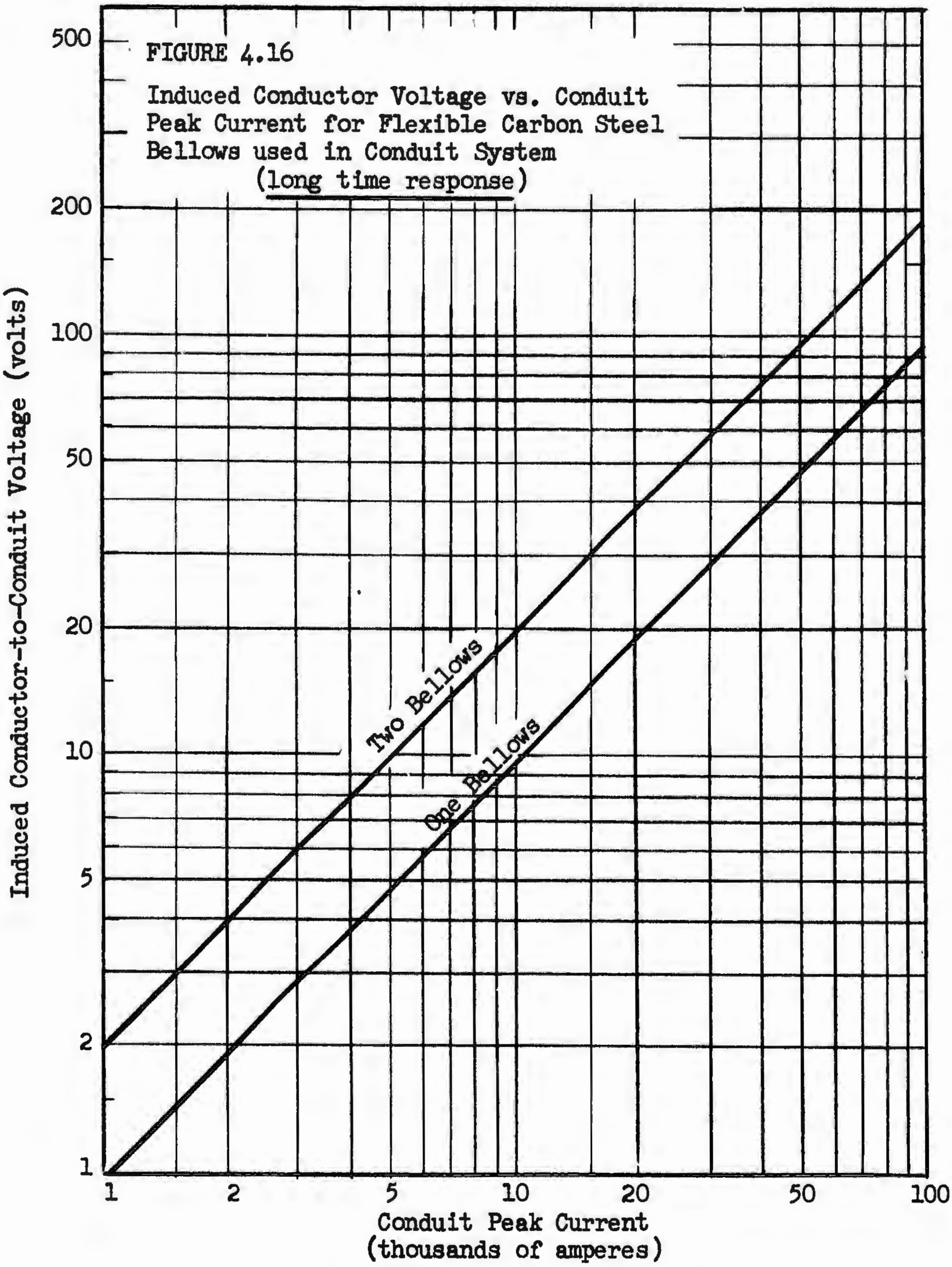


FIGURE 4.16

Induced Conductor Voltage vs. Conduit Peak Current for Flexible Carbon Steel Bellows used in Conduit System (long time response)

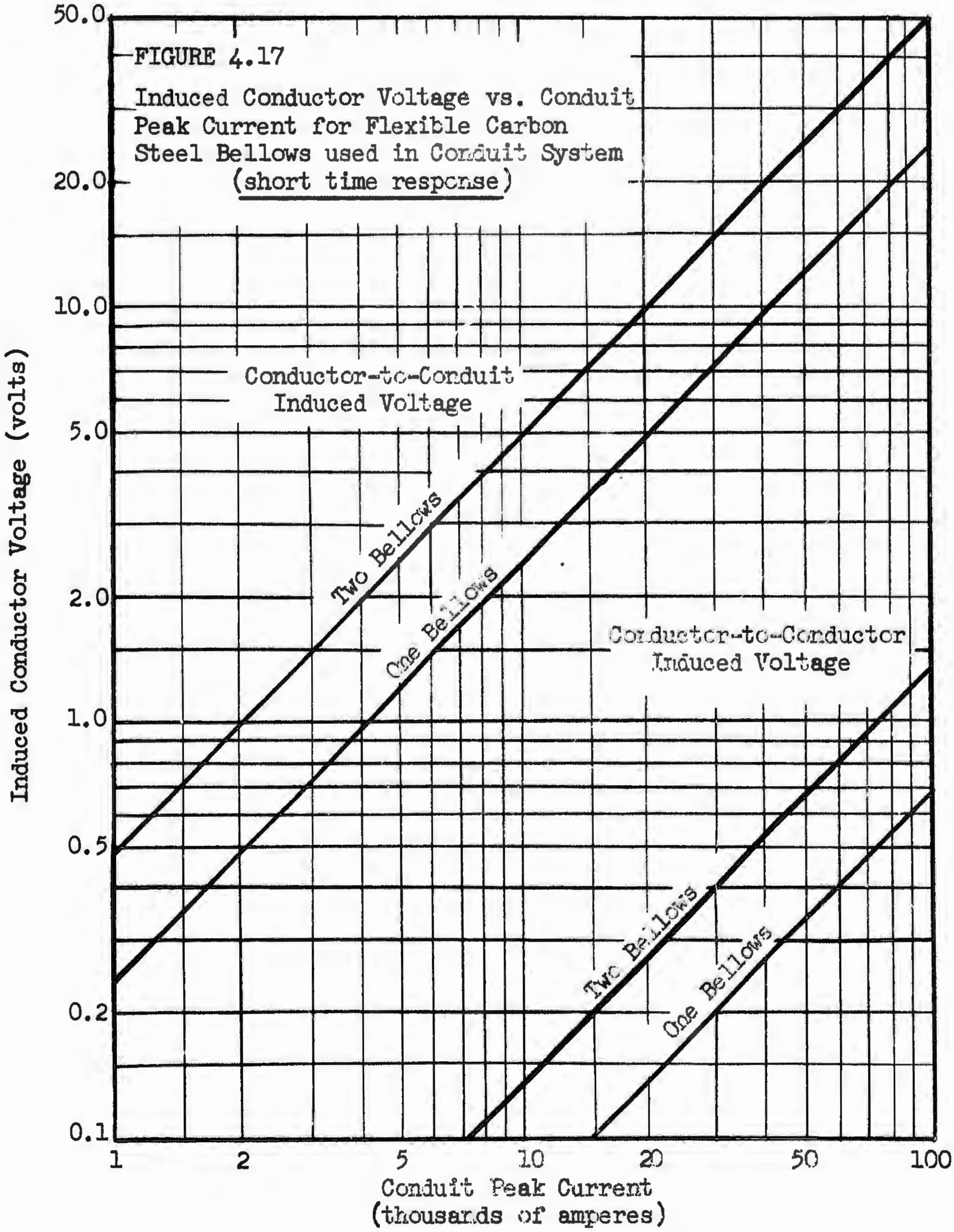


FIGURE 4.17
Induced Conductor Voltage vs. Conduit Peak Current for Flexible Carbon Steel Bellows used in Conduit System (short time response)
Conductor-to-Conduit Induced Voltage
Two Bellows
One Bellows
Conductor-to-Conductor Induced Voltage
Two Bellows
One Bellows
50.0
20.0
10.0
5.0
2.0
1.0
0.5
0.2
0.1
1
2
5
10
20
50
100
Induced Conductor Voltage (volts)
Conduit Peak Current (thousands of amperes)

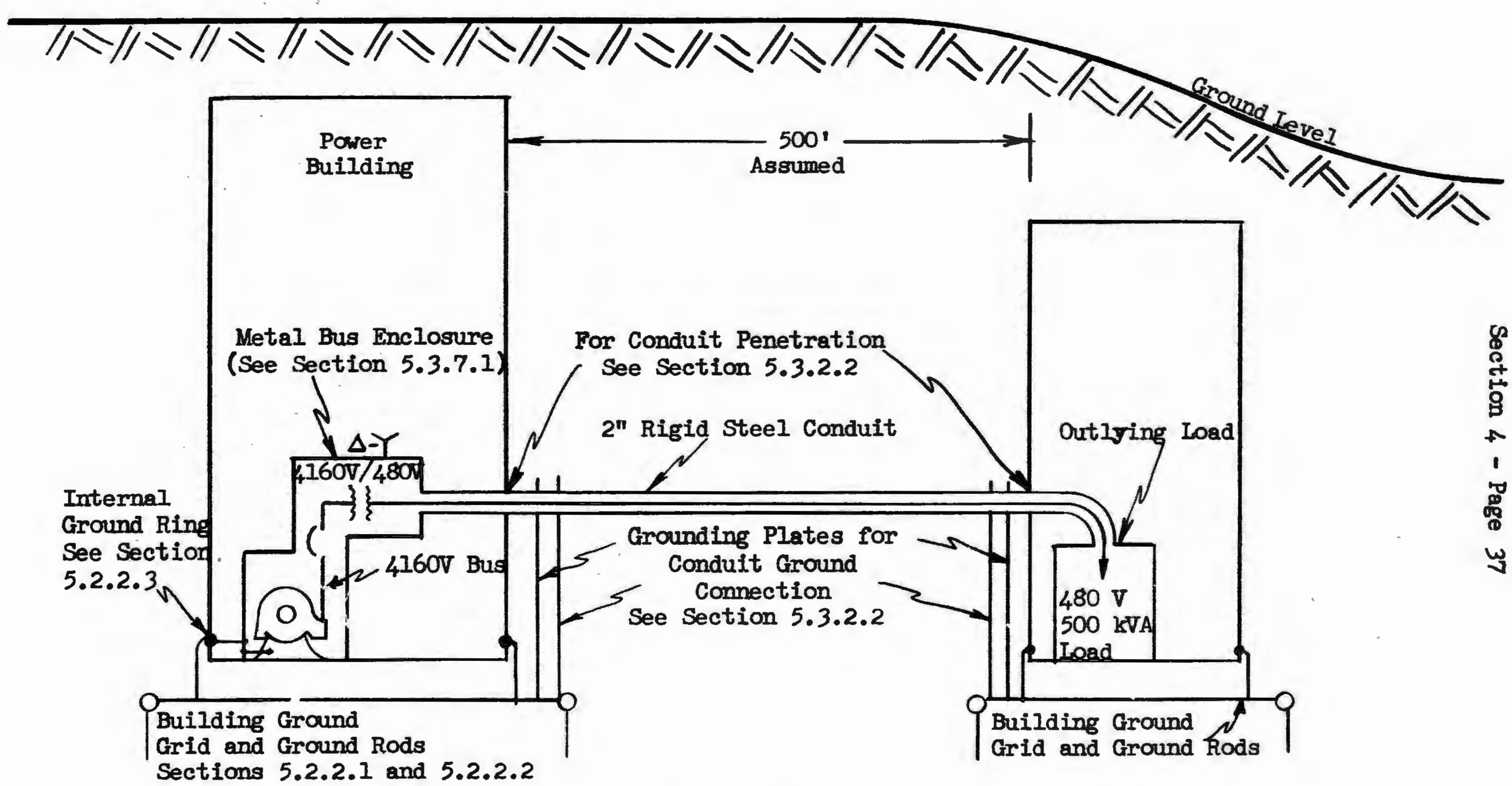


FIGURE 4.18 Typical Power Feed to Outlying Load Area

Reviewing Figure 4.16 it can be seen that the induced voltages from motors, motor contactors, transformers and the 480 volt conduit run all appear on the secondary side of the 4160 V - 480 V transformer in the power building. For reasons to be explained in the next example, the maximum load response need only be considered to calculate the resulting line-to-line overvoltage on the generator bus.

The calculation procedure is as follows:

First, change the maximum conduit induced voltage whether line-to-line or line-to-ground into a per unit value. This excludes the line-to-ground voltages induced because of the effect of conduit length, since these can cause no line-to-line generator bus overvoltage in a delta-wye system. The maximum induced voltage due to bends is 4.95 volts and that from couplings is 1.2 volts. In a worst case situation these induced voltages would be arithmetically additive and could result in a total induced voltage of 6.15 volts. This greatly exceeds the total line-to-line voltage of 0.22 + 0.14 = 0.36 volts as given in Table 4.7. Use this maximum induced voltage for calculations. The per unit line-to-neutral voltage for 6.15 volts, based on a 480 volt circuit voltage is:

$$\frac{6.15}{480 \times \sqrt{2}} \times \sqrt{3} = 0.0157 \text{ per unit L-N voltage}$$

Secondly, compare all per unit voltages injected at the transformer secondary and choose the maximum. Table 4.8 indicates that the maximum per unit response for equipment is 1.0, which is larger than the 0.0157 per unit voltage calculated for the conduit. This 1.0 per unit voltage propagates back to the generator bus and its effect upon the power system can be analyzed as follows: Refer to Table 4.3 and Figure 4.11 and relate the circuit under consideration to a similar circuit in the typical MSR power system diagram. The MSR cooling load circuit with injection location 3 is similar except for distance. This, however, will not significantly affect the transmitted transient voltage pulse. Enter Table 4.3

and find for a 1.0 per unit injection at point 3, the maximum per unit line-to-line generator bus voltage of $\frac{0.03}{\sqrt{3}}$. Calculate the line-to-line bus overvoltage as follows:

1.0 p.u. L-N voltage at load results in 0.0173 p.u. L-L voltage on the bus

$$V_{L-L\ (4160)} = 0.0173 \times 4160 \times \sqrt{2} = 102 \text{ volts}$$

To determine whether this primary bus transient voltage exceeds the primary bus performance requirement, compare this transient voltage with the allowable line-to-line primary bus overvoltage.

Assume now in this same example the possibility that one of the other feeder circuits connected on this bus is supplying power to a sensitive load operating at 480 volts. From the system response and propagation characteristics given in Section 4.4, the above calculated 0.0173 per unit voltage on the generator bus propagates unattenuated on a per unit basis to all load circuits. Therefore, the sensitive load circuit would experience a transient line-to-line voltage of

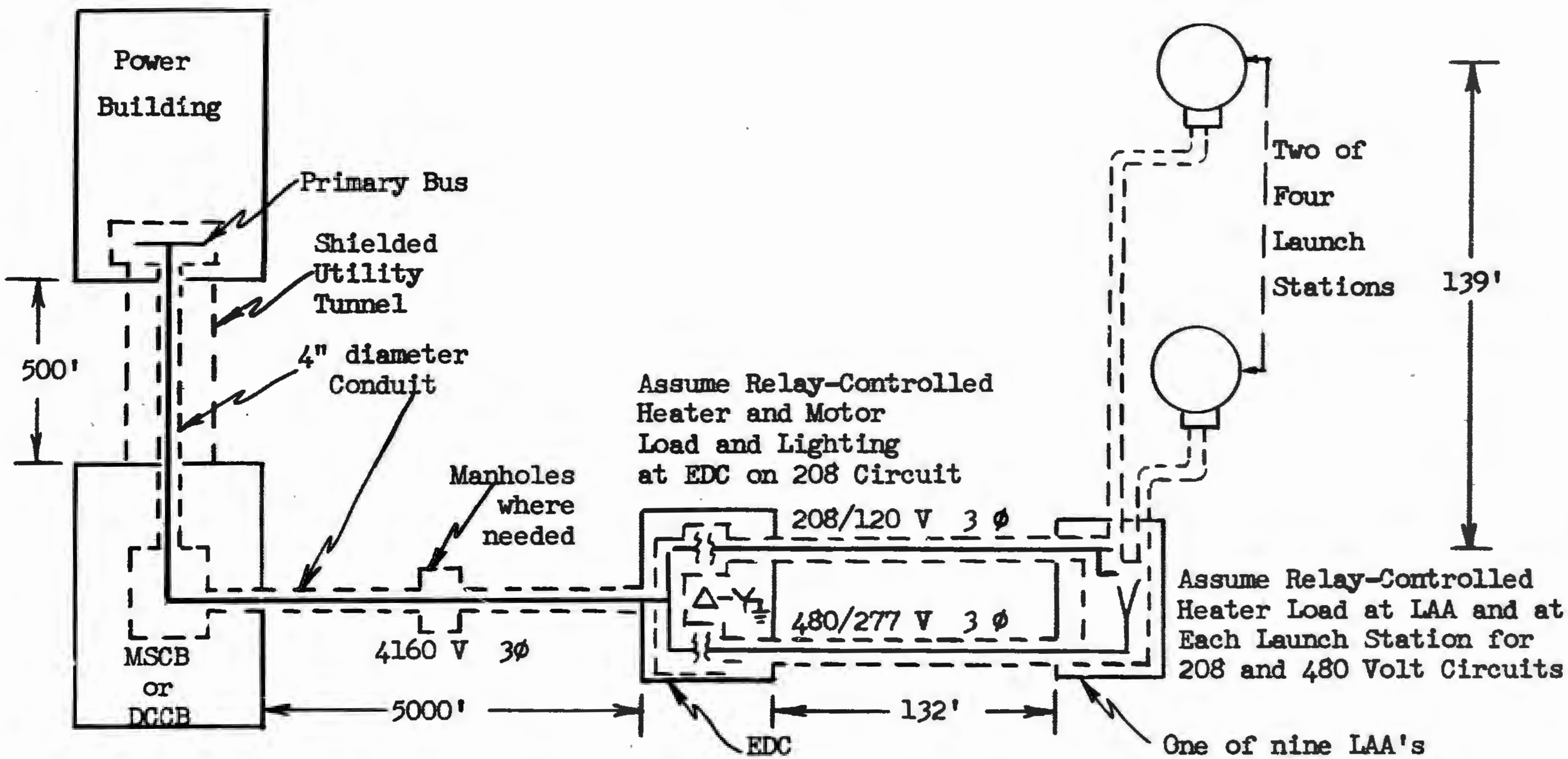
$$V_{L-L\ (480)} = 480 \times \sqrt{2} \times 0.0173 = 11.8 \text{ volts}$$

Refer again to Table 4.7. Consider the 15 volt line-to-ground induced voltage which appears on each phase conductor-to-ground on the 480 volt feeder. From Section 4.4 this L-G voltage will not cause a line-to-line or line-to-ground overvoltage on the generator bus when the pulse is transmitted through a delta-wye or wye-delta transformation. Since this is the case in our example, the induced voltage on the conduit conductors due to the conduit length effect can be neglected.

4.5.2 Response Calculations for Simplified Launch Area Antenna (LAA) Power System

For a more extensive illustration of the procedure used in calculating the effect of induced voltages in the power system in relation to the power system performance levels, consider the power circuits to the Launch Area as shown in Figure 4.19. First, list the susceptible circuits and

PLAN VIEW



The construction for bonding, grounding, penetrations, and shielding of the above system are assumed to be as stated in the appropriate sections of the protective measures report.

FIGURE 4.19 Typical Simplified Electrical Power System Feeder to Launch Area

equipment. To insure a complete listing, initially assume a magnetic field direction which gives the maximum induced voltage for all equipment and wiring. Starting at the primary bus, the susceptible items are:

A. the 500 foot run of 4-inch conduit in the utility tunnel between the power building and the missile site control building.

B. the 5000 foot run of 4-inch conduit between the missile site control building (MSCB) and the electrical distribution center (EDC).

C. the 4160-480/277 volt and 4160-208/120 volt delta-wye transformers at the EDC.

D. the relay-controlled heater and motor load at the EDC.

E. the lighting load at the EDC.

F. the 132 foot conduit runs between the EDC and LAA.

G. the relay-controlled heater load at the LAA.

H. the conduit run to each of the launch stations.

I. the relay-controlled heater load at the launch station.

By the method outlined in the previous example, the induced voltage for each of the above items can be translated into an equivalent per unit overvoltage at the primary bus in the power building. The resultant effective bus overvoltage response from this feeder is a function of all the individual circuit and component responses, Items A through I.

As a first approximation, one can, with a little experience, exclude those equipments and circuits whose overvoltage contribution is negligible. Motors and transformers, for example, have extremely small voltages induced in them. Relays are much more susceptible. Short conduit runs within buildings such as the conduit runs between transformers and motors and between transformers and lighting fixtures are other examples of items having negligible susceptibility. After a few of these calculations have been made, one can recognize these situations upon inspection.

Next, evaluate the responses of Items A through I, noting that Item A is contained within the shielded utility tunnel and assuming that Items B

through I are exposed to a magnetic field of 500 amperes/meter.

ITEM A. Assume that the utility tunnel has shielding which is 30 dB or greater. This would reduce the magnetic field strength to at least 16 amperes per meter. This magnitude of magnetic field strength would not induce voltages on the wiring of any significance. (See Section 4.5.3)

ITEM B. Assume that this run of 4-inch conduit is buried in earth having a conductivity of 4.5×10^{-3} ohms/meter. From the nomogram, Figure 4.2, this conduit in the 500 amperes/meter field would carry a peak current of 50,000 amperes. Therefore, we can determine from Figures 4.13, 4.14, and 4.15 the induced conductor-to-ground and conductor-to-conductor voltages in a manner similar to that given in the example of Section 4.5.1. These are shown in Table 4.9.

TABLE 4.9

INDUCED VOLTAGES ON CONDUCTORS IN 4-INCH RIGID STEEL CONDUIT

(H = 500 A/m; Conduit Current = 50,000 amps; Conduit Length = 5000 feet)
(Ground Conductivity = 4.5×10^{-3} mho/meter)

	Peak Induced Voltage		
Condition	Figure 4.13 50,000 amps	Figure 4.14 50,000 amps	Figure 4.15 500 amps/meter
Conduit (5000')	CG 150 Volts		
Three Bends *		CG 4.95 Volts CC 0.22 Volts	
499 Couplings*			CG 12.0 Volts CC 1.4 Volts

* - Twisted pair wire and three bends assumed
CG - Conductor-to-ground
CC - Conductor-to-conductor

The induced voltages given in the table will appear directly on the 4160 volt bus. The maximum line-to-line "short time" response is 0.22 + 1.4 = 1.62 volts. The maximum line-to-ground "short time"

response is 4.95 + 12.0 = 16.95 volts. The "long time" response, due to the effect of conduit length, is 150 volts; this appears on each phase conductor-to-ground.

Considering the short time induced voltages, choose the maximum response and convert to a per unit value; thus, the maximum response is a line-to-ground voltage of 16.95 volts. The per unit L-N voltage on the 4160 volt generator bus is then

$$V_{\text{per unit L-N}} = \frac{16.95}{4160 \times \sqrt{2}} \times \sqrt{3} = 0.005$$

The resultant per unit line-to-line 4160 volt generator bus induced voltage is calculated as follows:

Refer to Table 4.3 and note that for the generator bus, injection point 1, a 1.0 per unit L-N voltage results in a $\frac{1.4}{\sqrt{3}}$ per unit L-L voltage. Since the actual per unit L-N voltage was 0.005, the proportionately:

$$\frac{0.005}{1.0} = \frac{V_{\text{per unit L-L}}}{\frac{1.4}{\sqrt{3}}}$$

$$V_{\text{per unit L-L}} = 0.004$$

where $V_{\text{per unit L-L}}$ is the per unit line-to-line induced voltage on the generator bus due to an 0.005 per unit L-N voltage injection on the bus.

The 150 volt long time response does not cause a line-to-line induced voltage on the generator bus and will be discussed later.

<u>ITEM C.</u> Transformers, especially liquid-filled transformers having no exposed wiring on both the primary and secondary side, have very little induced voltage on the secondary. Figure 4.9 indicates that for a 500 ampere per meter field strength, the induced voltage is only 0.000045 times the rated voltage of the transformer.

<u>ITEMS D, E, G, and I.</u> Assume a motor at the EDC to have a dripproof

housing. From the design curve for motors, Figure 4.6, a 500 amperes per meter magnetic field strength results in a per unit induced voltage of 0.015. The induced voltage for relays, Figure 4.10, is 1.0 per unit for a 500 ampere per meter magnetic field. The dry-type lighting transformer induced voltage, which is 0.15 per unit, can be obtained from Figure 4.8. Note that the above items are a part of the total load on the 4160-208/120 volt transformer. The remainder of the load is assumed to be relay-controlled heaters at the LAA and at each launch station. These are listed as Items G and I which are also relays and will have the same induced voltage as determined above, i.e., 1.0 per unit voltage.

ITEMS F and H. Items F and H relate to the conduit runs from the EDC through the LAA to the launch stations. From a voltage injection point of view at the secondary of the 4160-208/120 volt transformer, the induced voltage on the wiring within the conduit can be considered as part of the 208/120 volt load. Assuming that the maximum conduit length from EDC to launch station is 271 feet, determine the maximum per unit voltage induced on these conductors as was done in the example in Section 4.5.1 and in Item B. This results in a L-N per unit voltage of 0.032 which appears between one phase of the 208/120 volt circuit and ground. The induced voltage which appears on each phase conductor-to-ground because of the conduit length effect will not cause any line-to-line overvoltage on the generator bus because of the delta-wye transformer connection.

There are nine such circuits of variable lengths running from the EDC to the launch stations. Only the circuit having the maximum length need be considered.

ITEMS C, D, E, F, G, H, and I - 208/120 Volt Load Circuits. Experimentally it has been found that the induced voltages from electrical equipment, components, and wiring, connected to a given transformer

secondary, act as parallel voltage sources each having internal series impedance. These voltages may approach as a maximum value the voltage that would be induced in the one device having the highest response if that device were open-circuited or isolated from the circuit. (Reference 2). Therefore, in the case of the 208/120 volt load circuit, the induced voltage used to determine the effective load circuit response at the primary bus is the largest induced voltage from any piece of electrical equipment, component, or wiring of the 208/120 volt load circuit. Since all the induced voltage values obtained from Figures 4.6 to 4.10 are open circuit values, they need only be compared and the maximum voltage selected. Table 4.10 shows this comparison.

TABLE 4.10

COMPARISON OF INDUCED VOLTAGES FROM VARIOUS LOADS ON 208/120 VOLT CIRCUIT

Items	Induced Voltage (per unit values)
Liquid-filled Transformer Secondary	0.000045
Motors	0.015
Lighting Transformers (dry-type)	0.15
Relays	1.0
Wiring	0.032

As can be noted from the table, the relay response is higher than any other item and is, therefore, used to represent the induced voltage contribution of the 208/120 volt circuit as it affects the primary bus overvoltage.

Now, to determine the per unit line-to-line voltage response at the primary bus in the power building, refer to Figure 4.11 and Table 4.3. Note that the missile farm feeder in Figure 4.11 has two transformers between the 208/120 volt circuit and the primary bus. In the

example cited, the primary bus voltage was stepped down to 208/120 volts with one transformer. Therefore, the response from the 208/120 volt load is transmitted to the primary bus as shown by voltage injection point 4. Table 4.3 indicates that a 1.0 per unit line-to-neutral voltage injection at point 4 results in a $\frac{0.02}{\sqrt{3}} = 0.0115$ per unit line-to-line voltage at the primary bus.

ITEMS D, F, and H - 480/277 Volt Load Circuit. Consider now the 480/277 volt feeder from the EDC to the LAA and launch stations. Assume that the only load is several relay-controlled heater circuits. The induced per unit voltage from relays in the 480 volt circuit will be the same as the 208/120 volt circuit which was 1.0 per unit voltage. The induced voltage resulting from the effect of conduit length and the number of bends and couplings for the 480 volt circuit will be similar as well. Therefore, as was the case with the 208/120 volt circuit, the induced voltage from the relays has the maximum response and propagates to the primary bus and appears as a 0.0115 per unit line-to-line voltage.

The final step in the calculations is to determine the total response of the MSL feeder at the primary bus. Listing the individual responses, we have:

	Per Unit L-L Response at Primary Bus
a. 5000 foot conduit run (R_1)	0.004
b. 208/120 volt load circuits (R_2)	0.0115
c. 480 volt load circuit (R_3)	0.0115

$$\text{Total Feeder Response } R = \sqrt{(R_1)^2 + (R_2)^2 + (R_3)^2}$$

$$R = 0.0167 \text{ per unit L-L voltage}$$

This per unit voltage would propagate unattenuated on a percentage basis to all other feeder and load circuits. Comparing this 0.0167 per unit L-L

voltage to an assumed 0.02 line-to-line performance specification on the generator bus, this particular feeder would not in itself exceed the specification. However, the simultaneous responses of all the system feeders must be considered. Assuming that the electrical system is composed of many such feeders, each contributing a certain induced primary bus overvoltage, the total contribution of all feeders can be calculated by an rms summing process:

$$\text{Total Primary Bus Response} = \sqrt{(\text{Feeder } 1)^2 + \cdot \cdot \cdot (n^{th} \text{ Feeder})^2}$$

If all feeders contributed 0.0167 per unit volts to the primary bus, then only one such feeder could be tolerated without deteriorating bus performance based on a 2% bus performance specification. If the bus performance requirement was 50%, a maximum of 867 such circuits could be tolerated.

It should be noted that in the example calculations, the relays were considered to have no shielding. If shielding were provided, it would considerably reduce the transient overvoltages at the bus. For example, if each relay were provided with a 20 dB shield, the resultant feeder response in the example would be reduced by a factor of almost four times. This means that approximately 20 such circuits could be operated without exceeding the assumed 2% performance specifications of the generator bus.

To complete the analysis of this assumed launch area feeder, consideration should be given to the induced voltages which appear on all phase conductors to ground due to the conduit length effect. In the case of the 5000 foot conduit run this induced voltage to ground is the same on all three phase conductors and, therefore, causes essentially no line-to-line voltage change. Referring to Section 4.4, this line-to-ground voltage will not propagate to any other load circuit if the step down transformation is a delta-wye, as is the case in the example. Likewise, the line-to-ground (conduit length effect) induced voltage from the 271 foot conduit run will not cause a line-to-line induced voltage on the generator bus because of the wye-delta transformation.

4.5.3 Supplementary Considerations for LAA Power System

Consider now for the LAA power system the possibility that conduit run penetrations at buildings dictate the use of flexible bellows to allow for some motion between building and conduit. This will affect the induced voltages on conductors within these conduit runs. To assess the effect of the addition of the bellows in terms of the overall system response, proceed as follows:

First, obtain a new response value for the conduit system. Assume that the 5000 foot, 4-inch conduit run between the MSCB and the EDC contains two such flexible bellows. The proper installation procedure for these bellows is given in Section 5.3.2.2. If proper installation is made, a 10:1 reduction in current can be expected between the conduit and bellows current. Therefore, if the assumed current on the conduit is 50,000 amperes, the bellows current is 5000 amperes. Referring to Figures 4.16 and 4.17, the induced conductor voltage due to bellows is given. For 5000 amperes, the conductor-to-ground long time response for two bellows is 9.8 volts. The conductor-to-ground and conductor-to-conductor short time responses are 2.4 and 0.07 volts, respectively. A new conduit response tabulation for the 5000 volt conduit run can now be made as shown in Table 4.11.

The new maximum short time response for the 5000 foot conduit run is 4.95 + 12.0 + 2.4 = 19.35 volts line-to-ground. Since the long time induced voltages appear simultaneously on all three phase conductors, no line-to-line voltage is developed and can be ignored in a delta-wye system. Converting the line-to-ground response to a per unit line-to-line voltage at the primary bus, we have

$$V_{\text{per unit L-N}} = \frac{19.35}{4160 \times \sqrt{2}} \times \sqrt{3} = 0.0057$$

Using Table 4.3

$$V_{\text{per unit L-L}} = \frac{0.0057 \times 1.4}{\sqrt{3}} = 0.0046$$

Secondly, use the same procedure to determine the new response from

TABLE 4.11

INDUCED VOLTAGES ON CONDUCTORS IN 4-INCH RIGID STEEL CONDUIT RUN CONTAINING TWO BELLOWS

(H = 500 A/m; Conduit Current = 50,000 amps; Conduit Length = 5000 feet)
(Ground Conductivity = 4.5×10^{-3} mho/meter)

	Long Time Response		Short Time Response		
Condition	Conduit Length 50,000 amperes	Bellows 5,000 amperes	Conduit Bends 50,000 amperes	Conduit Couplings 500 amps/meter	Bellows 5,000 amperes
Conduit (5000')	150 volts				
Three Bends *			CG 4.95 volts CC 0.22 volts		
499 Couplings *				CG 12.0 volts CC 1.4 volts	
Two Bellows		9.8 volts			CG 2.4 volts CC 0.07 volts

* - twisted pair and three bends assumed

CG - conductor-to-ground

CC - conductor-to-conductor

the 271 foot conduit runs with bellows between the EDC to the launch station. This new response will be much lower than the 1.0 per unit voltage for relays and, therefore, will not enter into the primary bus response calculations.

Finally, total the responses for MSL feeder at the primary bus.

$$\text{Response (R)} = \sqrt{(0.0046)^2 + (0.0115)^2 + (0.0115)^2}$$

$$R = 0.0169 \text{ per unit voltage}$$

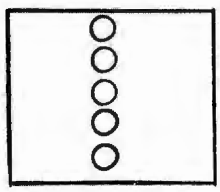
The use of bellows has very little effect on the overall feeder response.

In all the examples given thus far, a worst case situation was presented because it was assumed that only one conduit run existed between any two buildings and all the current flowed on this conduit. In all likelihood more than one conduit will exist between buildings and will be grouped and placed in the same underground trench or duct. If this situation should exist, the peak conduit current, as determined by the nomograph, Figure 4.2, used to calculate the conduit wiring response can be reduced by a factor dependent upon the number and arrangement of conduits in the group. Experimental and analytical results of several conduit grouping arrangements have indicated that outermost conduits in a group arrangement carry more current than innermost conduits. Therefore, to determine the current which is to be used for groups of conduit runs, refer to Figure 4.20. The factors given in Figure 4.20 yield conservative results. In the previous example, if five conduits were run between the MSCB and EDC in a vertical arrangement, the calculations would have been based on a peak conduit of $50{,}000/\sqrt{5} =$ 22,700 amperes.

4.5.4 Response from Conduits within Buildings

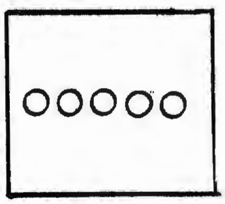
The illustrations thus far have not considered conduit within buildings. Normally the induced voltage from this source is negligible, but for the purposes of clarity, the two most basic and likely situations are explored:

1. Consider a power building with 500 feet of external conduit entering the building and continuing for 100 feet to the primary bus



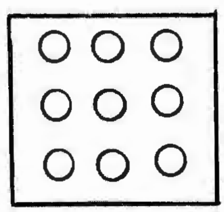
For a vertical conduit arrangement, the induced current on conduits, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by $1/\sqrt{N_V}$, where N_V is the number of conduits in the trench or duct.

A. Vertical Arrangement of Conduits in a Duct or Buried in a Trench



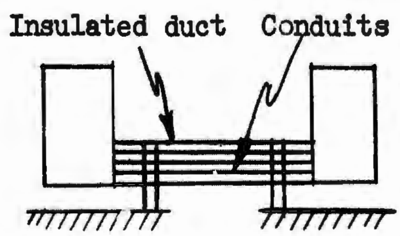
For a horizontal arrangement, the induced current on conduits, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by $1/\sqrt{N_H}$, where N_H is the number of conduits in the trench.

B. Horizontal Arrangement of Conduits in a Duct or Buried in a Trench



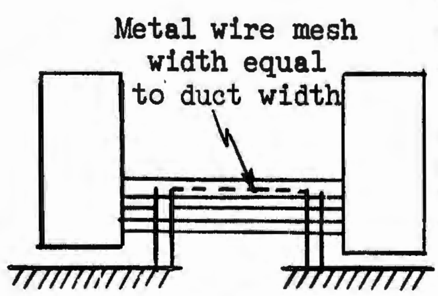
For a vertical and horizontal arrangement, the induced current on conduits, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by $1/\sqrt{N_V} \times 1/\sqrt{N_H}$, where N_V and N_H are as in A and B above.

C. Vertical and Horizontal Arrangement of Conduits in a Duct or Buried in a Trench



When conduits are placed in insulated ducts, the induced conduit current, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by 1/1.25 in addition to the factor given above relating to conduit arrangement.

D. Conduits in Insulated Duct between Buildings



When a wire mesh is placed above conduits and connected to the grounding plate at both ends of the duct, the induced current on conduit, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by the following factors in addition to those given above relating to conduit arrangement. For wire mesh 2.5 feet above conduit multiply by 1/2. For wire mesh 4.0 feet above conduit multiply by 1/3.

E. Conduit Ducts with Metal Wire Mesh Placed above Conduits in Duct

FIGURE 4.20 Physical Conduit Arrangements Affecting the Induced Current on Conduits and the Resulting Induced Voltage on Wiring.

enclosure. <u>The conduit grounding procedure at the building interface shall be made as shown in Section 5.3.2.2.</u> It has been experimentally shown that for this conduit grounding procedure, at least a 10:1 current reduction is established by the ground connection. For example, assuming 50,000 amperes on the external conduit, 5,000 amperes will continue on the 100 feet of conduit in the building. The resulting induced conductor voltage from the reduced current on 100 feet of internal conduit is negligible compared to the induced conductor voltage resulting from the external conduit current.

2. Consider conduit runs and loops within buildings not connected to external conduit. The induced current in these loops for various magnetic fields can be obtained from Table 4.1. As can be noted, conduit currents and the induced voltage contribution from these conduits are negligible.

4.5.5 Design Formulation Summary

A few illustrations of design procedure have been given which encompass the major problems which the designer will face and the major decisions he must make. The following procedural steps are listed as a guide:

1. Assume that maximum voltages are induced everywhere in the electrical system simultaneously.
2. For each feeder determine and list separately the open circuit induced voltage values for all electrical equipment, components, and wiring for all load circuits connected to the secondary of a transformer.
3. From the list in (2) above, choose the maximum induced voltage connected to the secondary of each transformer. Use this voltage to represent the response from the total load on that transformer which is then transmitted back to the primary bus.
4. For each feeder use an rms summing procedure for the induced

voltage from (3) above to determine the total feeder response at the primary bus.

5. For the total system use an rms summing procedure for all of the individual feeders. This value should be compared with system performance requirements.

5.0 PROTECTION TECHNIQUES

5.1 Application of Protection Techniques and Devices

The overall objective of Section 5.0 is to implement the power plant and facilities electrical systems protective recommendations presented in Sections 2.0 and 3.0. This is done by stating and illustrating in detail the requirements for system grounding and bonding, EMP shielding, and applications of various protective devices. Specific instructions are given to permit evaluation of a number of shielding and protection schemes and examples are cited. The theory and principles involved in these techniques are covered only as far as they relate to particular types of construction that satisfy criteria requirements; a broader treatment is contained in Section 10.0.

In Section 5.1.1 those protection techniques that relate to personnel safety are presented. Section 5.1.2 lists the applicable techniques relating to protection for the power plant and facilities electrical equipment.

5.1.1 Protection Techniques to Assure Personnel Safety

Because of the environment conditions of rapidly varying magnetic fields and sizable earth currents, conditions hazardous to personnel may exist unless proper precautions are taken. The rapidly varying magnetic fields can induce high voltages across open conducting loops formed by improperly grounded metal conduits, piping, equipment enclosures, and even metal structures. The earth currents can be expected to appear over a large area simultaneously and will tend to concentrate on any conductors encountered. Dangerous voltages will be developed at any points of comparatively high resistance along these conductors. It is, therefore, important from the standpoint of personnel safety that such earth currents be routed along controlled paths. These effects can be controlled and rendered harmless to personnel by applying the grounding and bonding techniques prescribed in Section 5.2.

Lightning strokes likewise constitute a possible threat to personnel, particularly above ground where electrostatically produced voltages tend

to appear at relatively small, elevated areas. Upon discharge, large currents (of the same order as those accompanying EMP phenomena) will also flow on conductors. The application of lightning protection is also covered in Section 5.2.

5.1.2 Protection Techniques to Assure Reliable Operation of Power Plant and Facilities Electrical Systems

The protection techniques applied to insure personnel safety will also benefit electrical and other equipment associated with the Power Plant and Facilities. This is especially the case for metal conduits containing electrical power, communications, and control wiring. A number of specialized protection techniques may be required to assure reliable operation, under tactical conditions, of the power plant and facilities electrical systems in addition to the grounding and bonding techniques given in Section 5.2. These are:

A. Methods of EMP shielding (Section 5.3).

B. Application of overcurrent and overvoltage protective devices (Section 5.4).

C. Application of filters (Section 5.5).

D. Circuit isolation techniques (Section 5.6).

5.2 <u>Grounding, Bonding, and Lightning Protection</u>

This section covers the grounding and bonding practices that must be followed to assure safety for operating personnel and to prevent equipment malfunctions or breakdowns caused by abnormal environmental conditions. The subsection on lightning protection gives detailed specifications on building constructions found effective in protecting against injury or damage from direct and induced lightning strokes, but does not include lightning arrester applications. These are outlined in Section 5.4.2. Supplementary reference information on the technical aspects of grounding and lightning protection is contained in Section 10.0.

5.2.1 General Requirements for Grounding, Bonding, and Lightning Protection

The general requirements for grounding, bonding, and lightning protection, applicable to all site structures, are as follows:

1. Ground system current shall be conducted along a controlled or predetermined path into the earth. This path shall be short and direct in order to have as little electrical resistance and inductance as possible.
2. In outdoor areas electrical equipment cases shall be interconnected directly with the buried grounding system.
3. In inside areas containing electrical equipment internal ground rings or ground buses shall be provided for grounding this equipment.
4. Bonding straps (intentional low resistance connections) shall be used to interconnect electrical equipment to minimize so-called "touch" and "step" voltages. (These are voltages that can exist between two pieces of equipment that an operator could simultaneously touch or voltages that might appear between a point where he is standing and equipment he could touch.)

The first step toward meeting these general requirements is to provide adequate paths to conduct current into the earth. This is usually accomplished by means of continuous counterpoise and/or ground rods driven deep enough into the earth to achieve a predetermined value of resistance between the grounding system and the earth. When considering lightning discharges, an equivalent (combined) ground resistance not exceeding five ohms is desirable. Since EMP ground currents may be of the same order of magnitude as lightning discharge currents, the equivalent ground resistance of each of the buildings constituting the complex should be approximately five ohms.

Building grounding may be accomplished in several ways. One method is

by means of ground rods driven at intervals around the periphery of the building and connected to the building steel structure and internal grounding rings. A second method is to lay a continuous counterpoise mat (consisting of buried bare conductors) around and out from the building and connected to the building structure and internal ground rings in the same fashion as the ground rods. The third method is to use a combination of the first two.

Ground rods have the advantages of having immediate and intimate contact with the earth, but the disadvantage of having to be driven at each and every point an earth ground is required, which introduces problems of placement in rocky soil or rock strata. The counterpoise has the advantages of being easy to connect and to install. The main disadvantage of a counterpoise is the elapsed time required for intimate earth contact to be established. By properly combining ground rods and counterpoise, the advantages of both can be obtained and the disadvantages can be largely eliminated. This approach was used for the specific recommendations which follow. Reference information for determining ground resistances of specific ground rod and counterpoise configurations is given in Sections 10.1.2 and 10.1.3.

5.2.2 Specific Recommendations for Grounding and Bonding

5.2.2.1 Ground Rods and Interconnections

The minimum requirements for EMP and lightning protection with respect to ground rods and counterpoise and their connections at structures and other locations are as follows:

1. Copper-clad or stainless steel rods shall be driven to depths at least 10 feet below equipment level or counterpoise, whichever is lower. The spacing between rods shall be 50 feet or less, with one rod at each building corner or one at each of the two diagonal corners if the peripheral distance between diagonal corners is less than 50 feet.

2. The ground rods shall be interconnected to the counterpoise mat buried in the earth.
3. The ground rods shall be interconnected to the reinforcing steel rods, welded wire fabric, cr metal plate shielding; also to the internal grounding rings of the structure.
4. More extensive counterpoise systems may be required at locations where rock strata or boulders prohibit driving ground rods. (These shall be considered as special cases.)

5.2.2.2 Counterpoise Mats and Interconnections

Counterpoise mats used for the external grounding of structures shall consist of a continuous conductor having the equivalent conductivity of a No. 1/0 AWG copper wire buried in the ground around and under the foundation of the building below lowest equipment level and shall extend about 96 inches away from its walls or foundation. Locations of ground rods and counterpoise for a typical structure are shown in Figure 5.1. Note the metal current dispersion plates which are welded to the counterpoise grid at conduit entrances.

Counterpoise mats shall be required under the MSCB or DCCB and the utility tunnel the same as the one underneath the Power Plant.

Minimum requirements for counterpoise interconnections shall be considered satisfied when the following conditions are met:

1. Counterpoise mats shall be interconnected with building shielding, if used, whether it consists of metal plate, reinforcing steel rods (rebars), or welded wire fabric at each corner of the building and at each ground rod location. The resultant distribution shall place connections no more than 50 feet from each other, except on structures with dimensions less than 25 feet on a side; in this case a minimum of three interconnections of shielding and mat shall be made.
2. If rebar shielding or welded wire fabric shielding are <u>not</u> being

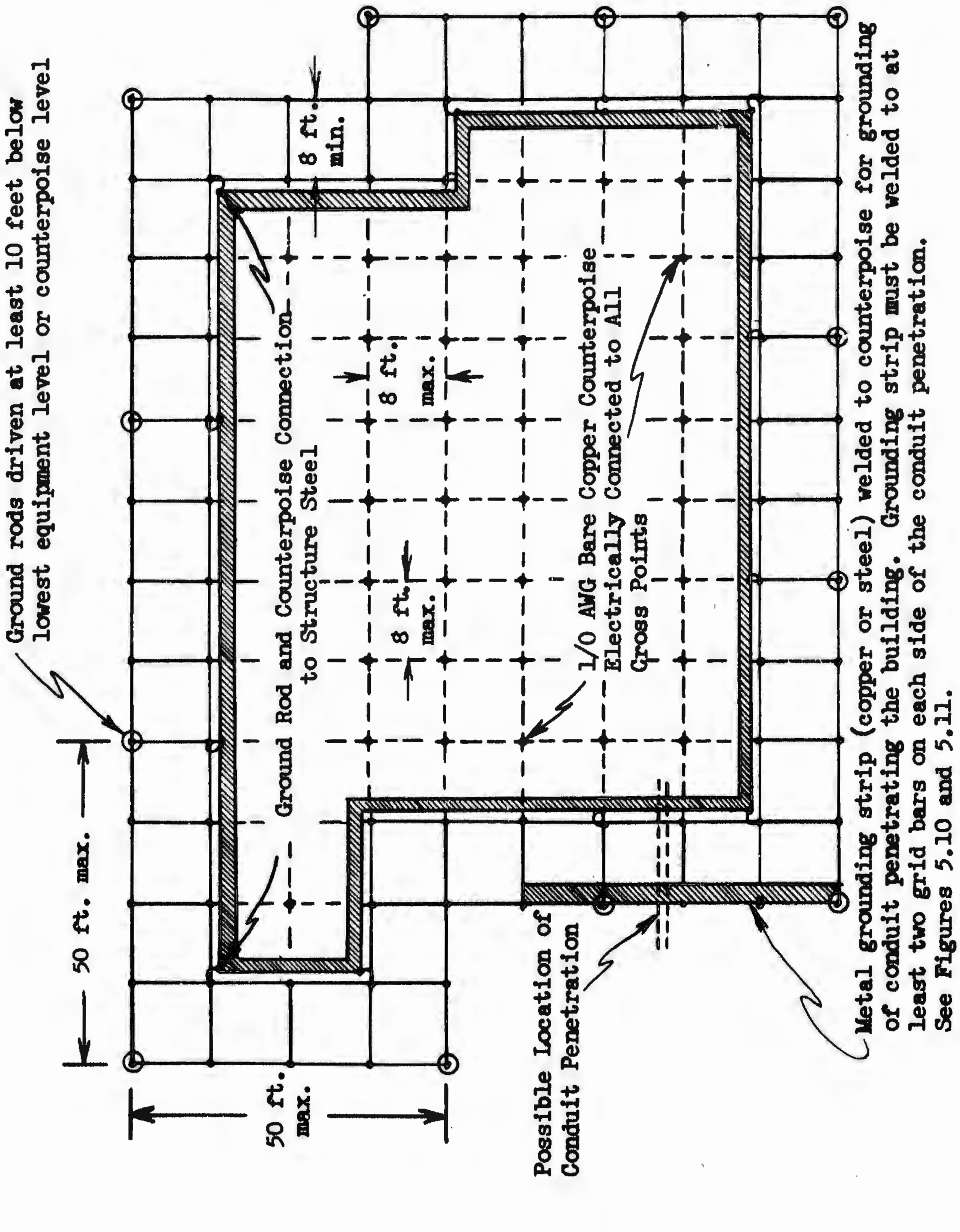


FIGURE 5.1 Ground Rods and Counterpoise Layout (typical)

used, but a single course or multiple courses of rebars are used to reinforce the structure, the outermost course of vertical construction rebars shall be welded at each joint so that each rebar forms an electrically-continuous vertical grounding conductor. This is shown in detail for several building configurations in Figure 5.2. Note that any horizontal construction rebars which are a part of a vertical side must be made electrically-continuous and connected to the electrically-continuous vertical construction rebars. This is shown in Figure 5.2B. Note also that the outermost rebars are connected to the lowest horizontal rebar and to the counterpoise. The inner construction rebars need not be electrically-continuous and need not be grounded. Each rod joint shall have a minimum welded length at least three times the rod diameter or utilize the threaded couplings illustrated in Figure 5.31. Connections from these vertical rebars forming grounding conductors shall then be made to the grounding system (counterpoise and rods) by one of the following methods:

a. Welding the lowest course of horizontal rebars to form an electrically-continuous loop around the periphery of the structure and welding each vertical rebar to this loop. This horizontal rebar loop shall then be connected to the counterpoise mat with 1/0 AWG copper bonding straps at the intervals given in Item (1) above.

b. Welding all vertical rebars to the lowest course of horizontal rebars and then welding this course of rebars to form an electrically-continuous loop around the periphery of the structure; also provide additional electrically-continuous crossties between lowest course rebars, tying to the counterpoise mat and grounding system as outlined in (a) above.

c. For long buildings provide additional electrically-continuous

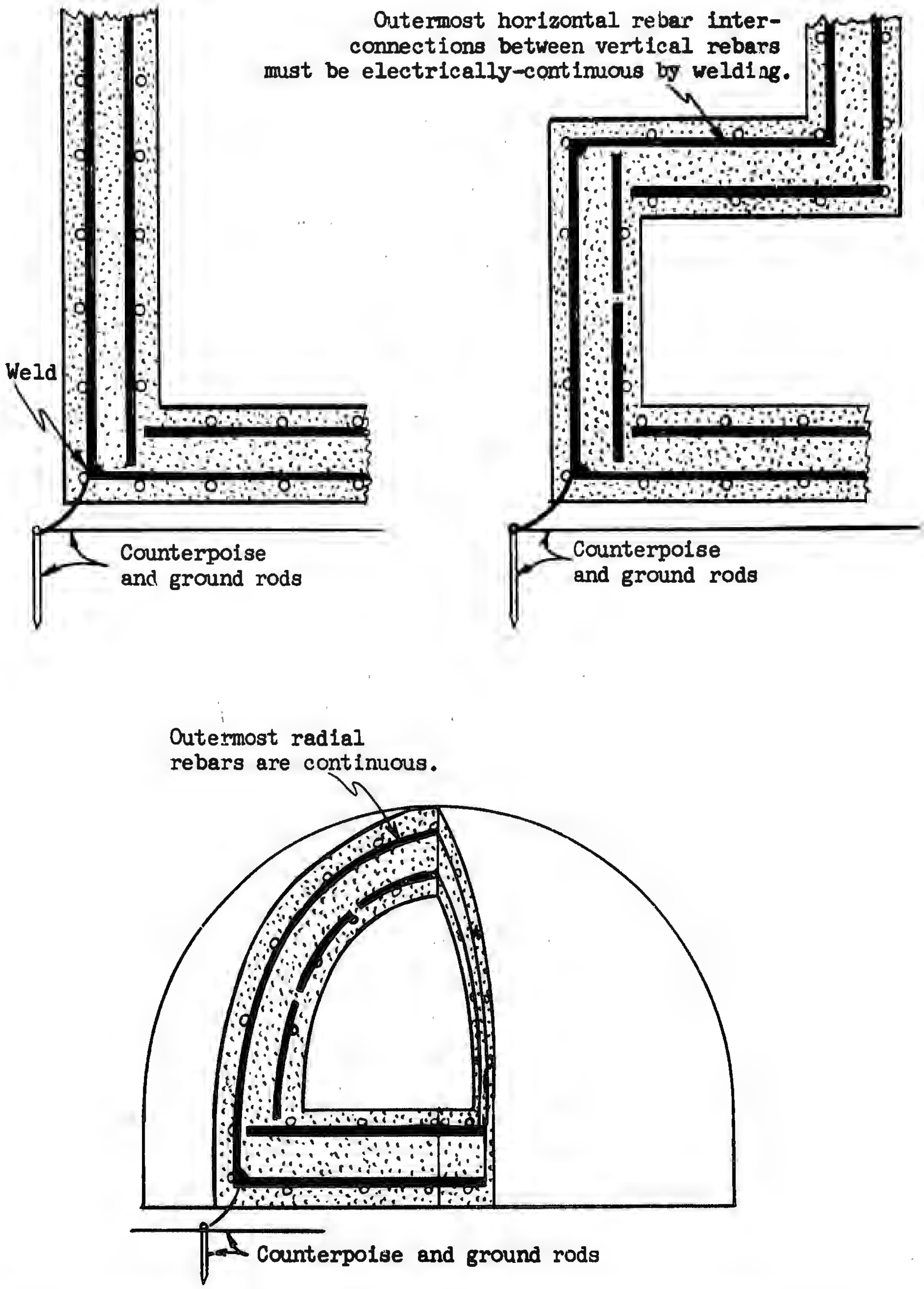


FIGURE 5.2 Connection of Outermost Rebars for Electrical Continuity for Various Shaped Buildings

horizontal ties across the counterpoise at the intervals provided by Item (1) above, bonding each vertical grounding rebar to the lowest course rebars forming the peripheral loop, tying to the counterpoise at the intervals specified in Item (1).

3. All grounds, internal grounding rings, etc. established within the structure area for any purpose shall be interconnected with the counterpoise. Special equipments and devices such as Electro Explosive Devices may require grounding systems electrically separate from the NEMP-Power-Lightning ground system. These separate systems are permitted providing they are interconnected by means of a low voltage protective device (see Section 10.3) to limit any voltage differences to safe levels.
4. Additional connections shall be made at any confluence of building services to provide a direct path for current via the large, external ground. The connection pattern may be shifted to accomodate service concentrations.

5.2.2.3 External and Internal Connections to the Grounding System

This section covers the manner in which connections shall be made to the grounding system, construction details for internal grounding rings, supplementary ground buses and risers, as well as the specific techniques for bonding and grounding certain kinds of equipment. It is presented in the eleven subsections that follow.

5.2.2.3.1 Grounding and Bonding Connections

Grounding and bonding conductors shall be run as directly as practicable. Avoid placing such conductors in iron or steel conduits or in raceways. If, however, this construction is necessary, the grounding or bonding conductors shall be connected to the conduit or raceway at each end of the run. (This restriction does not apply to power wiring which has an internal ground wire whose utilization shall be considered mandatory.)

5.2.2.3.2 Precautions for Making Connections to the Grounding System

All reasonable precautions shall be taken to protect the ground system conductors and connections against physical and electrolytic damage. In the presence of moisture, where grounding and bonding conductors are of dissimilar metals, connections should be made up and tested for low resistance, then coated with a waterproof material, and finally taped to prevent galvanic action. A recommended procedure for accomplishing this is as follows:

1. Clean surface or grease.
2. Apply rubber to metal cement such as U. S. Royal #5038.
3. Apply electricians rubber tape.
4. Wrap with pressure-sensitive vinyl tape.

Another suggested method would be to use a bimetal terminal collar which would be placed on the steel conduit, rebar, or other steel member which must be electrically connected to the copper counterpoise. The steel portion of the bimetal collar would be welded to the steel member and a 1/0 AWG copper conductor would be brazed to the copper portion of the bimetal collar and extend to the copper counterpoise and also be brazed at this point. The collar connection assembly should be waterproofed and taped to prevent galvanic action.

5.2.2.3.3 Internal Grounding Rings

Internal grounding rings are recommended as a convenient means to achieve multiple paths for ground currents, to facilitate bonding, and to assure low voltage drops. The following requirements relate to internal grounding rings and their interconnections:

1. An internal grounding ring consisting of a continuous No. 2 AWG bare copper conductor or an equivalent copper bus shall be installed around the inside wall of each building or room within a building arranged to accomodate large electrical equipment layouts. It may alternately be located close to the ceiling, housed

in a non-metallic protective sheath or set into the floor to reduce the possibility of physical damage and body contact. The internal grounding ring shall be interconnected to the counterpoise mat as shown in Figure 5.3 at the intervals given below.

2. For buildings with largest dimensions 25 feet or less having only one internal grounding ring (Figure 5.4A), four interconnections at the corners shall be made. If there is more than one internal grounding ring, a minimum of two interconnections to the counterpoise system shall be made from each grounding ring. (Figure 5.4B)
3. Larger buildings will require more interconnections, but in no case shall spacings exceed 50 feet.
4. Although these interconnections would normally be spaced symmetrically, judgement may suggest shifting the pattern.

5.2.2.3.4 Supplementary Grounding Buses

Supplementary grounding buses consisting of No. 2 AWG bare copper conductors or equivalent strips shall be used whenever necessary to provide a more accessible means of connecting metallic objects to the internal grounding ring.

5.2.2.3.5 Risers

Risers of No. 2 AWG bare copper conductor or an equivalent copper bus shall be used to interconnect the internal grounding rings between floors. (Figure 5.3). Risers shall be located at, or as close as possible to, the points of connection of the internal grounding ring and the counterpoise jumpers. These points are marked with an "x" on Figure 5.4. Internal ground rings may also be grounded to the outermost vertical rebars in which case risers are not required. (Figure 5.3)

5.2.2.3.6 Interconnection of Metal Objects inside Buildings

All sizable metal objects such as utility piping, metal stacks, tanks, motor frames, pumps, metal doors, etc., shall be bonded to the ground system with No. 6 AWG bare copper conductors. Banks of metal objects, such as

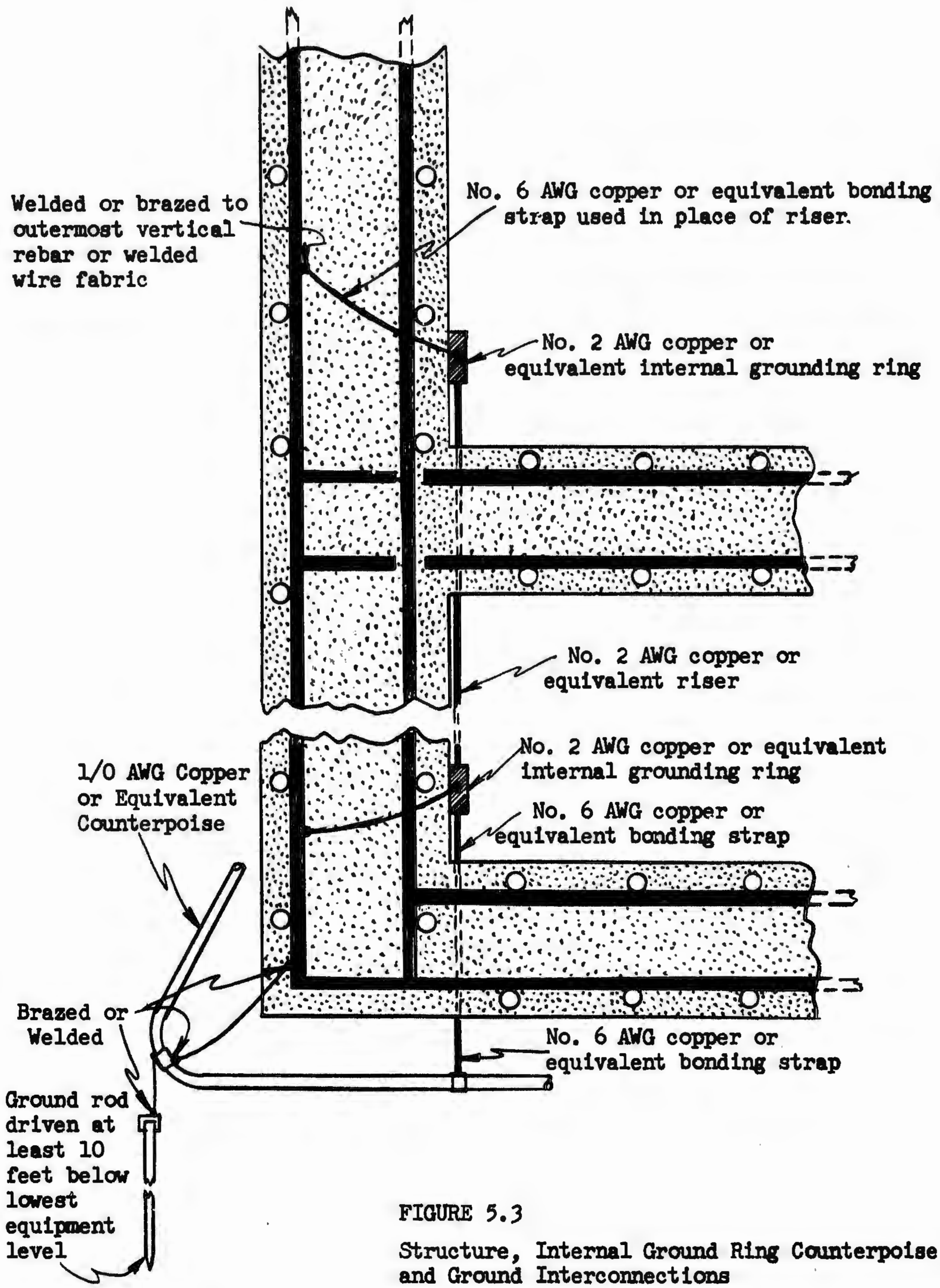


FIGURE 5.3

Structure, Internal Ground Ring Counterpoise, and Ground Interconnections

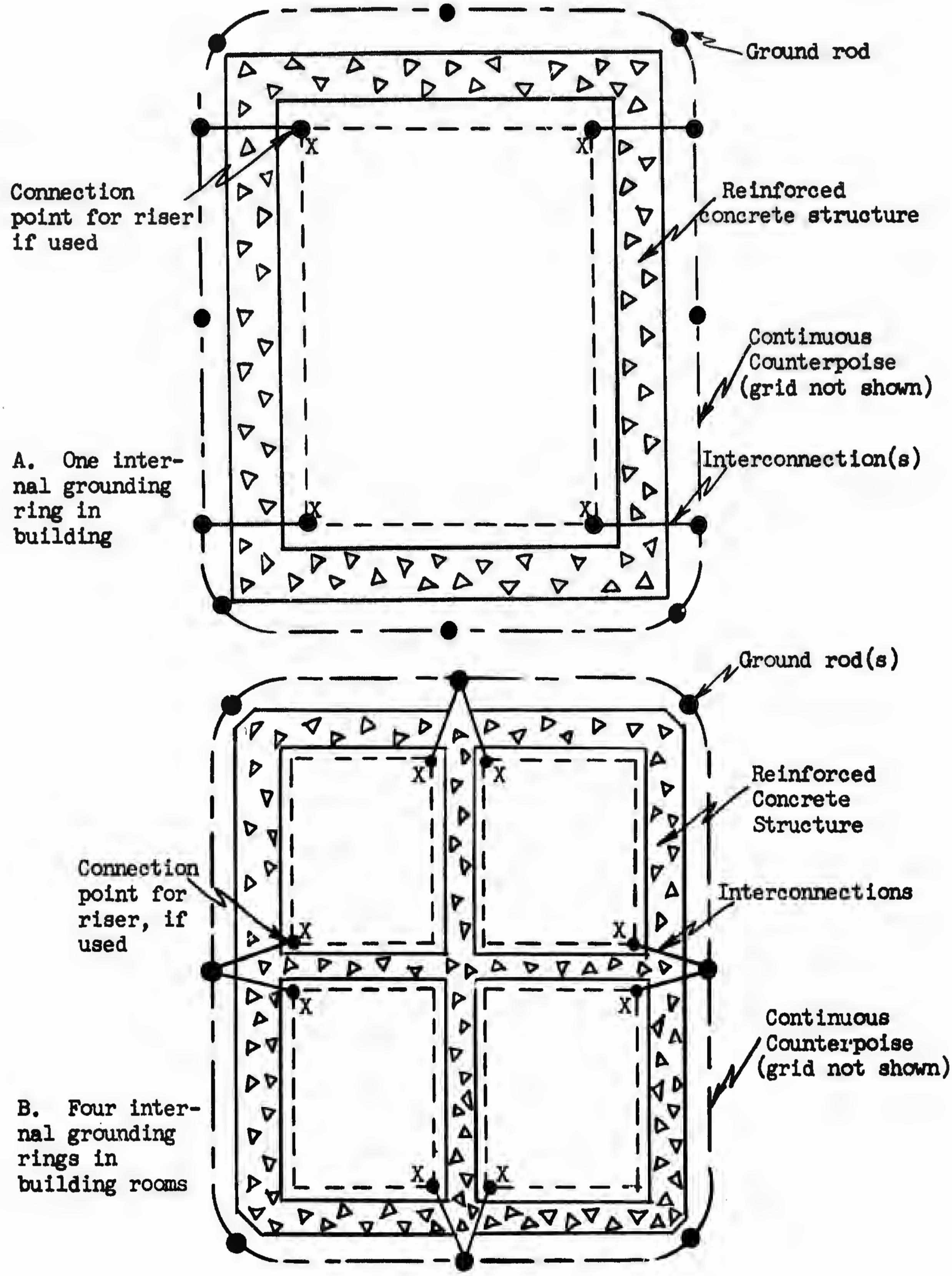


FIGURE 5.4 Interconnections between Internal Grounding Rings and Counterpoise

continuous racks of equipment having reasonably good electrical continuity may be bonded to the ground system at each end of the bank or row with No. 6 AWG bare copper conductors. Structural members of antennas and metal wave guides installed inside the building shall be bonded to the internal grounding ring with No. 6 AWG bare copper conductors.

5.2.2.3.7 Connection of Conduits, Cable Sheaths, and Shields to Ground

All conduits and the metal armor sheaths and shields of power and communication cables shall be bonded at their end points to the grounding system using No. 6 AWG bare copper conductors. In the utility tunnel all conduits, bus enclosures, and cable shields shall be connected to the counterpoise at the power building/utility tunnel interface.

5.2.2.3.8 Connection of Generator Cable Shields and Associated Junction Boxes and Enclosures to Ground

Each generator shall be connected to its associated switchgear and module auxiliary transformer by an armored cable or a bus assembled in a ventilated metal enclosure. Terminals, including stress cones, shield grounds, and terminal lugs, should be prepared to factory specifications. The EMP design requirements illustrated in Figure 5.5 shall be followed:

1. Cable shields shall be continuous between generator junction boxes, intermediate junction boxes, or circuit breaker enclosures and continue inside the enclosures.
2. The ventilated enclosures shall be grounded at the generators, circuit breaker housings, and any intermediate junction boxes.
3. Generator neutrals, if brought out, shall be connected to their grounding device by insulated shielded or non-shielded cables contained in metal enclosures in the same fashion as the phase cables.
4. Industry practice of connecting a 0.25 µF surge-sloping capacitor between each phase terminal and equipment ground at each generator is required. These capacitors and their connecting wiring shall be placed within the generator housing or in a separate shielded enclosure. (Figure 5.5)

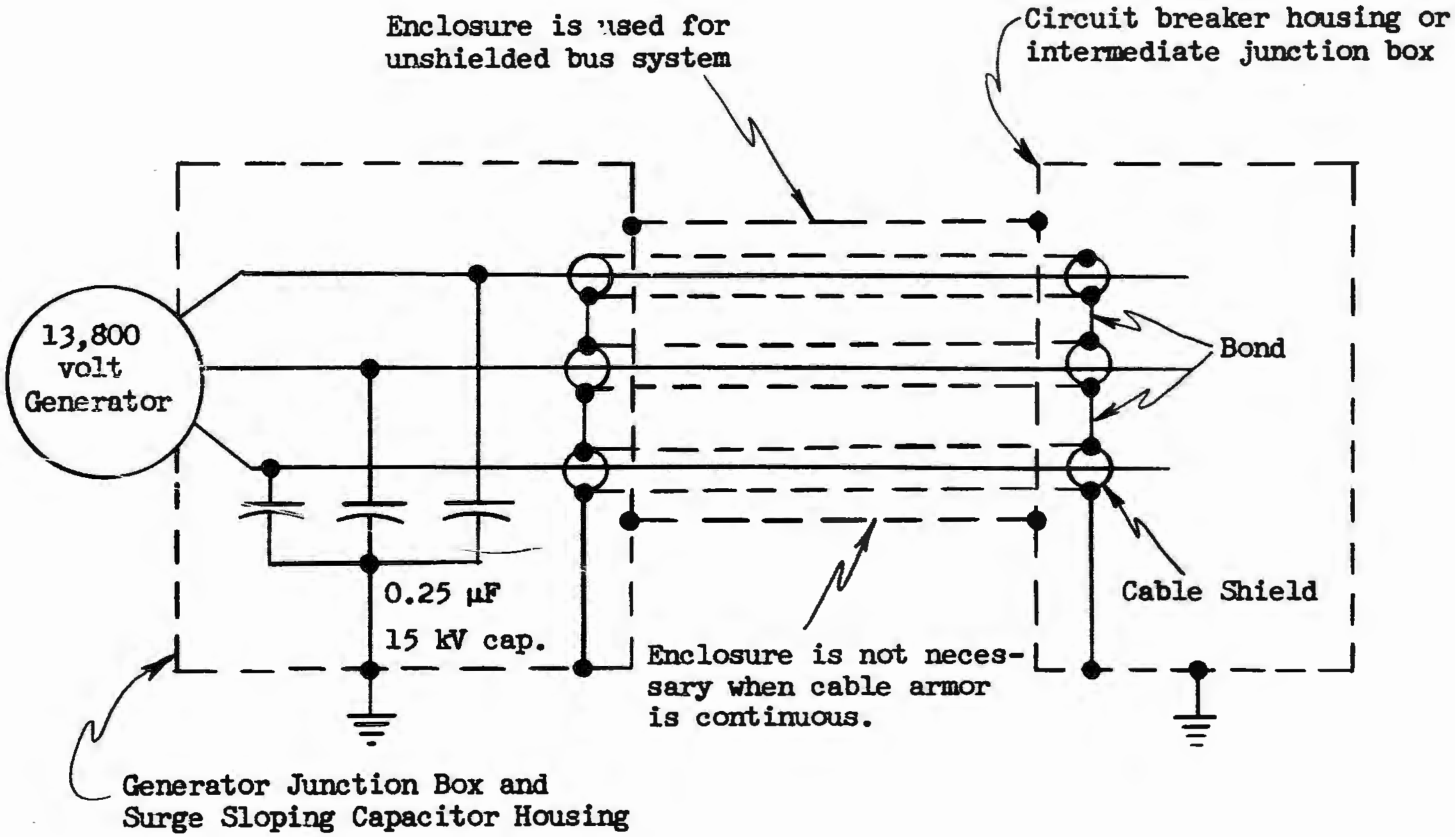


FIGURE 5.5 Bonding and Grounding Requirements for Generator Cable Shields or Ventilated Cable Enclosure

5.2.2.3.9 Connection of Shielded Enclosures to Ground

Shielded enclosures shall be connected to the common grounding system via the internal grounding ring. Connections may be bolted with mating surfaces making metal-to-metal contact. Connections should be welded in corrosive atmospheres. Conduits shall be electrically continuous between enclosures in order to form a completely shielded system. Details are illustrated in Figure 5.6.

5.2.2.3.10 Connection of Transformer Secondary Neutral to Ground

Secondary neutrals of transformers shall be connected to the internal grounding ring. No other connections shall be made between the neutral and the grounding ring. Where the same loads may be served by two or more transformers or banks, the transformer neutrals shall be connected to the same insulated neutral bus and this bus shall then be connected to the internal grounding ring at only one point.

5.2.2.3.11 Grounding Continuity for Non-metal Piping Sections or Insulating Joints

In the event that metal utility piping runs contain non-metal sections or insulating joints, the insulated sections or joints shall be electrically connected by bridging with bonds having an equivalent conductivity of 1/0 AWG copper. Bonding connections shall be made as outlined in Section 5.2.2.3.2.

5.2.2.4 Bonding Practices for Conduit Runs to Outlying Facilities

This section outlines specific practices required for bonding conduit sections at manholes and splice boxes.

Figure 5.7 defines a typical conduit run interconnecting point A at an underground access tunnel with point B at a remote building. It will be assumed that manholes or splice boxes are necessary in the run.

Figure 5.8 shows the typical construction for conduits at manholes and splice boxes. Requirements are as follows:

1. Manholes shall consist of a steel casing with a continuously welded

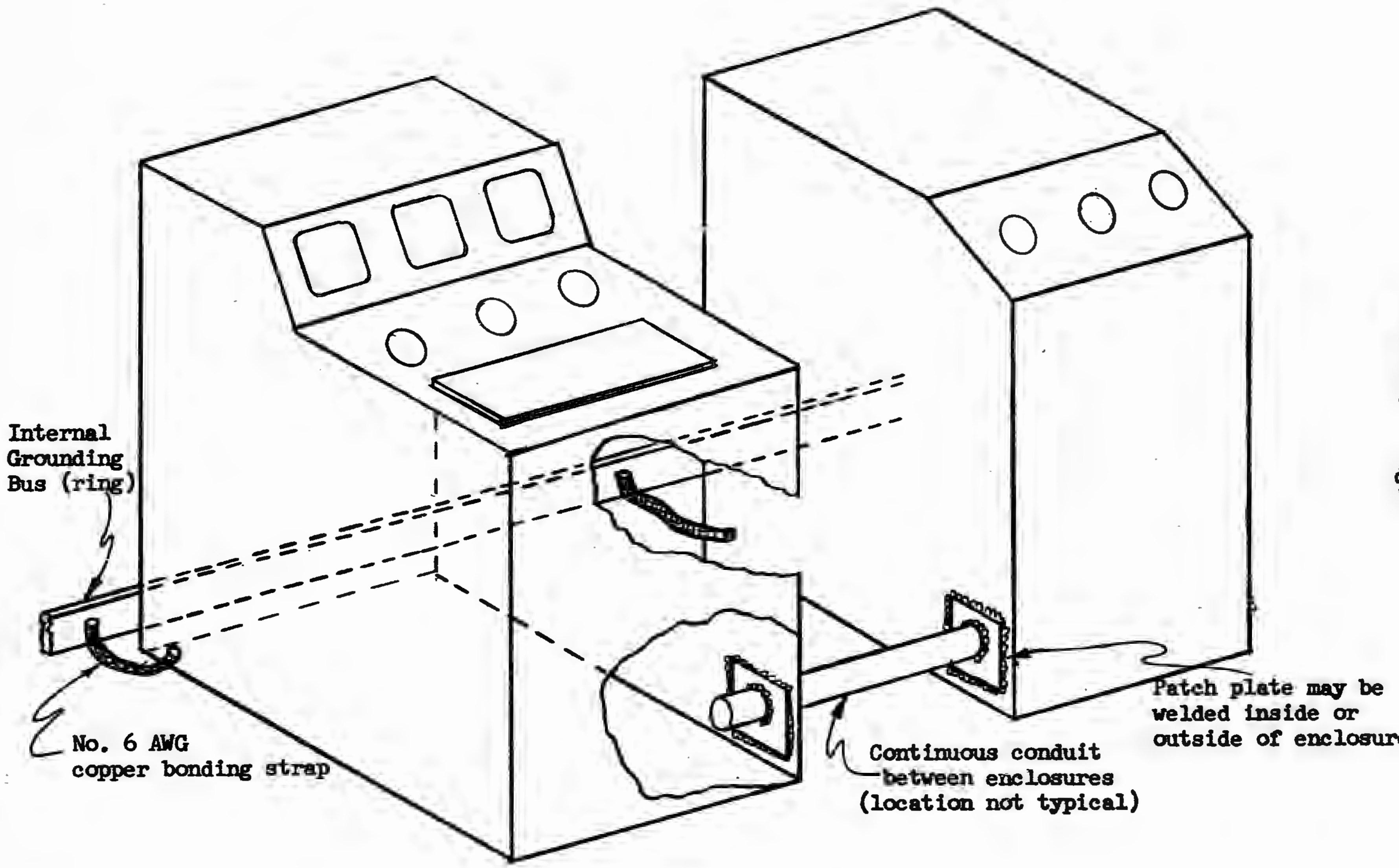


FIGURE 5.6 Connection of Shielded Enclosures to Ground

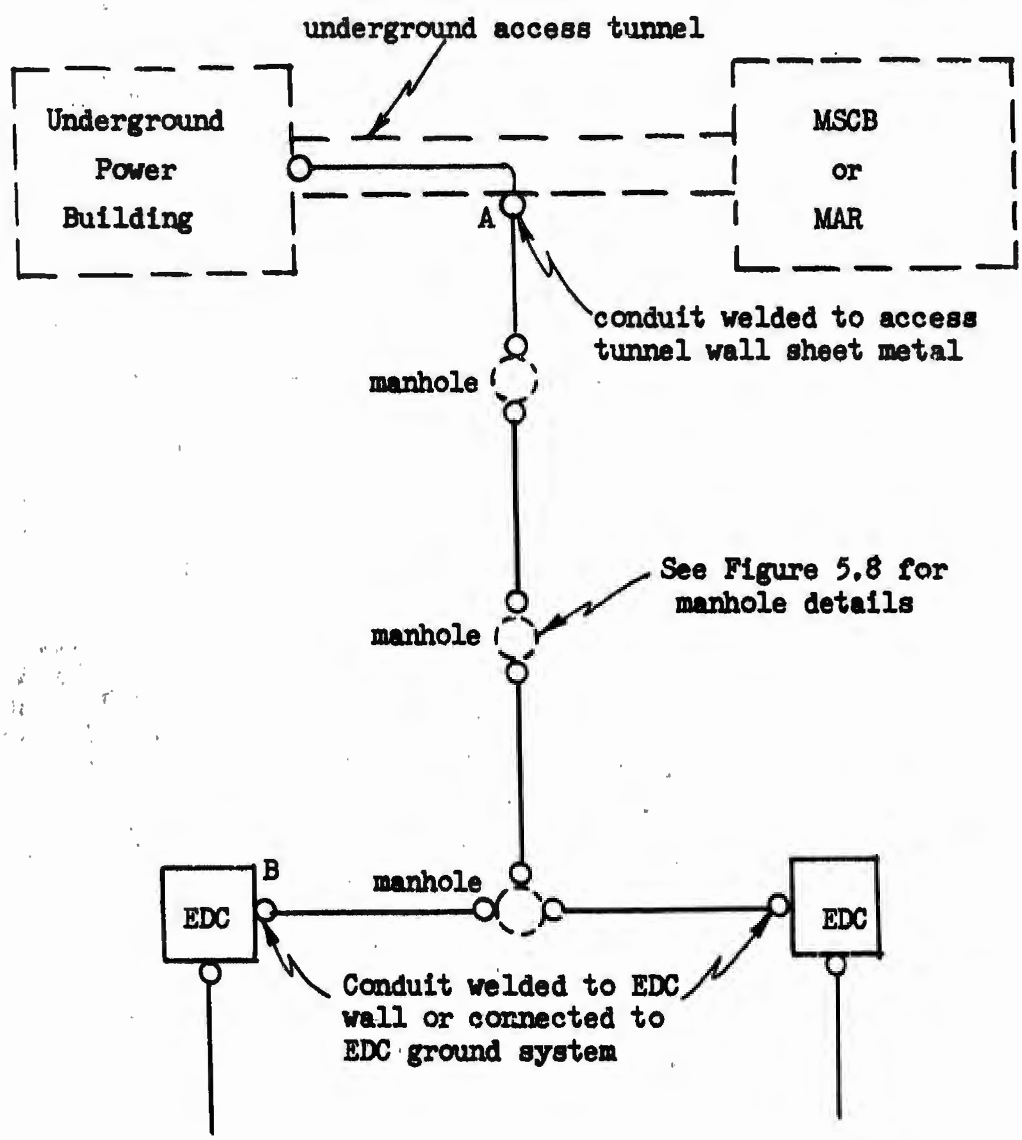


FIGURE 5.7 Defining Interconnecting Conduit Runs, A to B

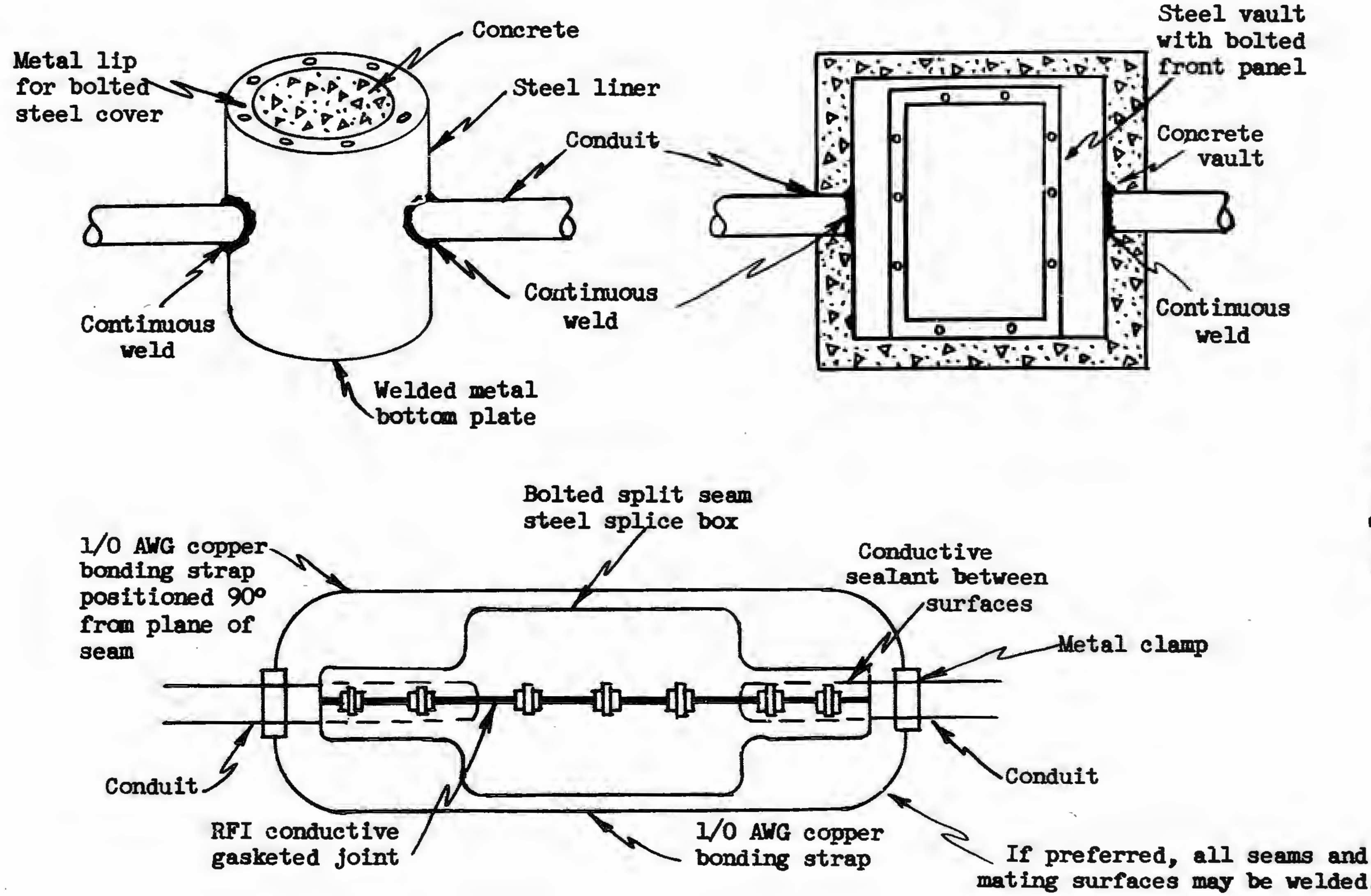


FIGURE 5.8 Manhole and Splice Box Details

steel bottom plate and a continuously welded steel top flange surrounding a concrete vault. The cover plate may be either bolted or welded to the top flange.

2. On bolted-cover manholes, conductive gaskets treated with conductive sealant shall be used between the flange and cover.
3. Conduits terminating at a manhole shall be attached to the steel casing by a continuous weld.
4. Cable sheaths and/or cable shields shall be electrically continuous at any splices made in manholes or in splice boxes.
5. Splice boxes may be of the bolted, split-seam type provided with conductive gaskets treated with conductive sealant or the mating surfaces may be continuously welded.
6. Two 1/0 AWG copper bonding straps, positioned 90° from the plane of the parting surfaces of the splice box, shall be clamped or suitably attached.
7. The interior of the splice box should remain watertight.

The construction relating to bonding of the conduit penetrations at the underground access tunnel, point A, and at a remote building, point B, is covered in Section 5.3.2.2.

5.2.3 Lightning Protection

5.2.3.1 Lightning Protection for Power Plant and Facilities

Unless otherwise specified, the construction details of the lightning protection system for the power plant and facilities shall conform to Handbook No. 46, Code for Protection Against Lightning, National Bureau of Standards.

The lightning protection system shall be selected on the basis of the building construction described below. This system is considered adequate because of the low risks involved. Overlapping of several different protection systems is permitted, especially when building construction is governed by other requirements such as radio frequency shielding and debris

protection which may result in exterior treatments differing from those described in the handbook.

5.2.3.1.1 Lightning Protection for Metal Roofed and Metal Clad Buildings

Regardless of its purpose, if any metallic building sheath is made electrically continuous as noted below, the building shall be judged as incorporating the most certain of the protection techniques:

1. A metal or metal shielded roof shall be made electrically continuous through bonding, whether it is constructed of fabricated or interlocking sections, panels, plates, or otherwise.
2. The edge of a metal or metal shielded roof shall be bonded to the nearest external ground counterpoise with No. 1/0 AWG bare copper wire or equivalent.
3. Sections of metal gravel stops shall be bonded to the metal roof via grounding straps having the equivalent conductivity of No. 1/0 AWG copper wire to assure electrical continuity.
4. Where both the roof and side walls of a building are metal clad and not electrically interconnected, they shall be made electrically continuous by bonding roof to side walls using No. 1/0 AWG bare copper wire or equivalent straps spaced as indicated below. The metal sheathing shall then be connected to the external grounding ring (counterpoise and ground rods) by means of bonds of No. 1/0 AWG bare copper attached to the lower edges of the metal siding. Spacing of all these bonding straps shall conform to the requirements of Section 5.2.2.

5.2.3.1.2 Lightning Protection Masts

When the roof of the building to be protected is of non-metal construction, lightning protection shall be provided. In this event, the building(s) involved shall be considered as "most important cases", as defined in the National Fire Protection Association's Handbook No. 78, page 43, and the cone of protection required is such that the radius of the base is equal to

the height. (Figure 5.9). An installation utilizing lightning protection mast(s) providing cone(s) of protection that encompass the entire building area shall be judged as providing superior lightning protection than that afforded by unshielded, reinforced concrete construction. Alternatively, non-metal roofs may be protected by installation of lightning air terminals in accordance with Part II of the National Fire Protection Association's Handbook No. 78. These means are less effective, however, than that provided by metal roofed structures conforming to Section 5.2.3.1.1.

Masts located on a facility roof are more economical than freestanding ones; such masts shall be placed at a point beyond the antenna(s) which will not interfere with their radiation pattern(s).

If down leads are used with a mast, at least two shall be provided having the maximum possible separation from each other. Down leads shall be of not less than No. 2 AWG copper conductors for mechanical strength, and each shall be bonded to the turret or roof steel at no less than two points. Each down lead shall be directly bonded to the counterpoise.

5.2.4 Environmental Deterioration

5.2.4.1 General

Environmental deterioration is the process by which metal objects and structures undergo chemical combination with oxygen and other deteriorating chemicals in their environment. The scope of the protective measures in this section will be concerned with the corrosion of steel or similar ferrous metal objects for the conduction of electricity or magnetic flux; copper, cuprous alloy, aluminum or aluminum alloy objects such as sheets, rods, pipes, and wires used for the conduction of electricity and non-electrical structural metal parts, usually of steel, that either suffer corrosion from the presence of the electrical parts or promote corrosion of electrical parts. Technical details of the corrosion process and the various protection methods to allay corrosion are fully covered in Section 10.0.

The significance of corrosion in the present context is that it can

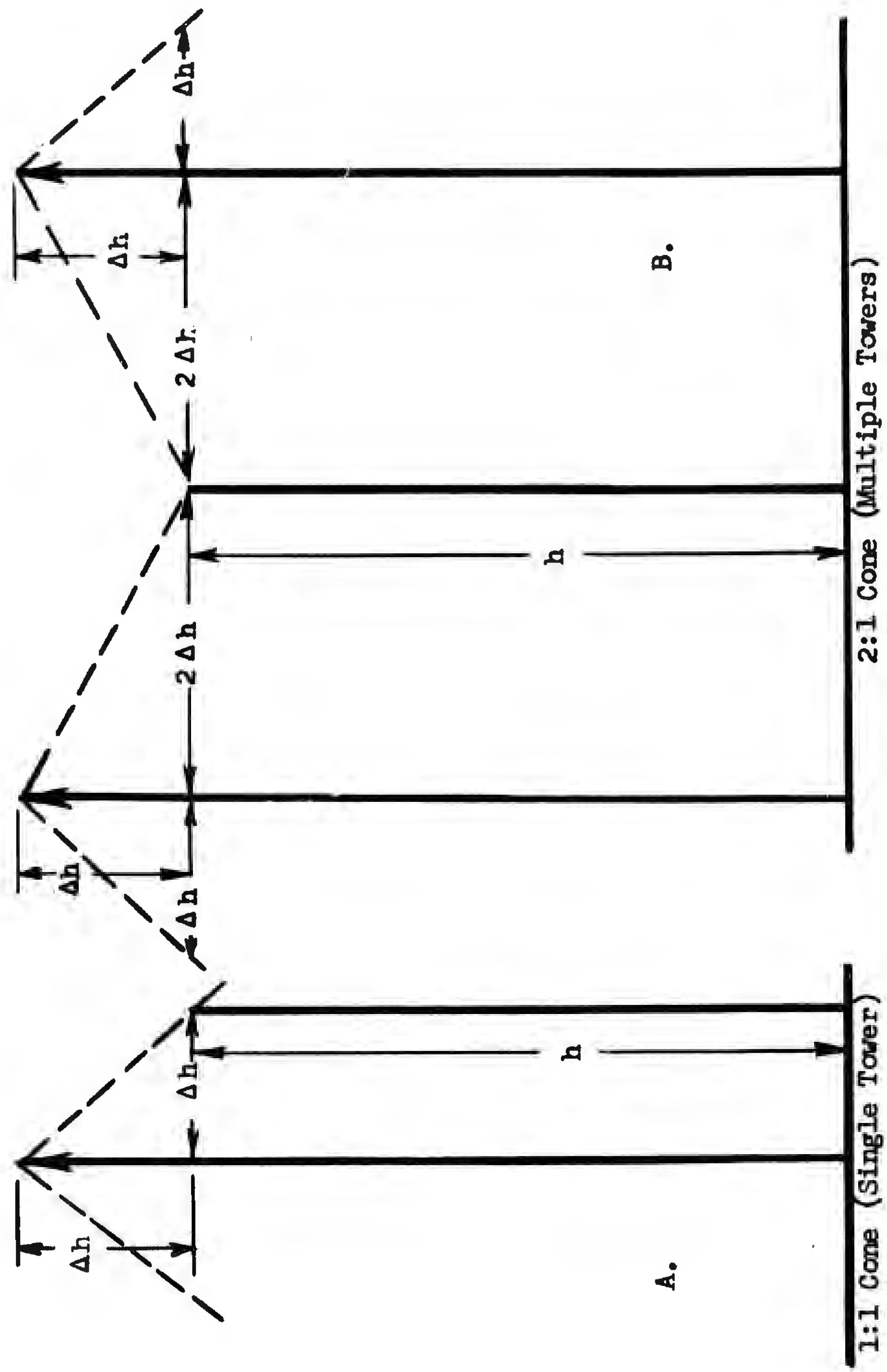


FIGURE 5.9 Cone of Protection Criteria

cause a loss of cross-section of the corroded parts making them inadequate for their intended current of flux-carrying purpose or structurally weak. An example of this weakening is the interruption of circuit continuity with the development of high resistance in a circuit because corrosion has caused fracture of a conductor or loss of metallic contact at joints or bonds in a conductor.

5.2.4.2 Specific Recommendations for Buried or Submerged Equipment

Environmental deterioration of buried or submerged equipment is greatly dependent upon soil and water conditions and the recommendations given below are for average soils and waters and average corrosive conditions:

1. It is specifically recommended that only grounding system conductors (counterpoise) and ground rods have direct contact with the earth.
2. All other buried or submerged parts such as structures, tanks, pipes, and conduits should be prevented from having direct earth or water contact. This can be accomplished by either coating or imbedment in concrete. Both of these methods will be discussed in detail.

COATING. When it is desired to protect a piece of buried equipment from galvanic corrosion by insulating it from earth contact, it is usually inadequate, and even harmful, to insulate it with thin coatings such as paint. This is because such coating will have small holes and imperfections and nearly all the galvanic corrosion represented by the electrochemical reaction will be concentrated at these small areas with consequent rapid corrosion through the exposed section.

The need to protect extensive underground piping systems such as gas and oil pipelines and large buried structures such as storage tanks has led to practices that have proved effective which are applicable to electric power systems. Protection methods, therefore, may involve both the electrical components of the underground system, as well as components

that are independent of it, and are of interest here because current established by the electrical grounding system may tend to promote corrosion of an independent system.

In soils and waters that are nearly neutral chemically (pH = 7) and where stray currents are not present or are bucked-out by electric cathodic means, zinc is an efficient protective coating for steel pipe. Hot-dipped zinc coatings of two ounces per square foot of surface are effective, but non-metallic coatings are more generally used. Of the large variety of coatings available, some are suitable only for mild protection.

Bituminous materials consisting of coal-tar pitch or natural asphalts are often used for coating. The asphalts have a wider temperature range between softening and embrittlement than coal-tar pitch, but are slightly susceptible to oxidation and more soluble than pitch in petroleum oils. The width of the temperature range for a coating is particularly important during shipment, because a cold coating may crack or chip and a warm coating may partially melt in transit. Coatings sometimes are formulated to best resist the temperature range and environment expected during transit. Coal-tar enamels are available in formulations containing plasticizers which make them suitable as coatings over wide temperature ranges. Asphaltic coatings with various additives such as sand, gilsonite, asbestos fibres and other fillers are available.

The principle criteria for choosing a coating are temperature range between softening and embrittlement, resistance to water penetration, and permanence under soil stress. Coatings can be applied at the factory or in the field. The following apply to coatings in the class of bituminous material:

1. Dipped coatings, or applications less than 1/16 inch thick, are of little value.
2. Reinforcing of the coating by asbestos roving or fibreglass fabric at least 1/8 inch thick is desirable.

IMBEDMENT IN CONCRETE. Where corrosive conditions are severe, Portland cement concrete coatings should be applied. This is usually done by field application of at least two inches of well-tamped concrete free of chloride admixture around the pipe or buried structure. Removable wood or metal forms are used to surround the equipment when the concrete mixture is emplaced. After setting and drying, it is desirable to coat the concrete with hot asphalt before back filling. Concrete encasement like this may develop hairline cracks. These have to be repaired periodically by cleaning and filling with tar. This form of protection is effective under very severely corrosive conditions and will last for many years.

In the presence of extremely severe conditions such as stray currents, the concrete imbedment may have to be supplemented by cathodic protection. Detailed information concerning cathodic protection techniques and requirements is presented in Section 10.0.

5.3 EMP Shielding

This section covers general aspects of EMP shielding, discusses precautions governing the use of conduit as shielding for power and other circuitry, and outlines the techniques of applying and evaluating various methods of shielding large structures, rooms and equipment enclosures, taking into consideration the effects of openings and penetrations.

5.3.1 Introduction

In a complex electrical-electronic installation such as the power building and the connected facilities, there will be equipment and circuitry of varying susceptibility to electromagnetic pulses, but with proper shielding, the system performance can be kept within acceptable limits.

The subject of shielding is presented in several parts:

1. Definitive approaches to shielding and attenuation.
2. Principles of the shielding process.
3. General rules applicable to all shielding techniques.
4. "Overall" versus "local" shielding practices.

5. Separate descriptions of shielding techniques proven effective in reducing environmental magnetic and electric fields to levels that will not adversely affect the system. These include ranges of application, construction details, and methods of calculating shielding effectiveness under various field conditions, including the effects of penetrations and openings.

5.3.1.1 Shielding and Attenuation Definitions

The approach to shielding against pulsed magnetic fields is essentially the same as shielding against any magnetic field. The basic concepts of shielding actions involve both dispersion of magnetic flux away from areas to be protected and dissipation of magnetic field energy. Enclosing susceptible equipment in metal enclosures and containment of all wiring within metal conduit or metal enclosures will reduce the voltages induced.

In determining the amount of attenuation provided by EMP shielding, it is difficult to define attenuation in a generally applicable, valid manner, because voltages induced in wiring and equipment depend upon many factors and resultant wave forms can be quite complex. (Shielding affects the peak amplitudes of waves as well as wave form, particularly the rise time of these peaks.)

Shielding attenuation, as defined in these protective measures, is 20 times the logarithm of the ratio of the H-field strength that would be present at a point without shielding to the H-field strength that would appear at the same point and at the same time with shielding. Shielding attenuation is expressed in terms of decibel (dB) units, determined by the following equation:

$$\text{Shielding Attenuation (dB)} = 20 \log \frac{H_1}{H_2}$$

where H_1 is the magnetic intensity at some point in the field without shielding,

and H_2 is the simultaneous magnetic intensity at the same point

in the field with shielding.

Protective measures prescribed in Sections 2.0 and 3.0 have evolved from evaluations using the shielding methods presented below.

5.3.1.2 Shielding Principles and General Rules

Basically shielding against magnetic field pulses consists of enclosing the region to be protected within an electrically conducting shell. The magnetic pulse flux tends to concentrate initially on the outside of the enclosing shell, then progressively penetrates to the inside of the shell as the pulsed field encompases it. If the shell is electrically continuous, the voltage induced in the shell by the pulsed magnetic field forces a current around the shell. This current produces a magnetic field which opposes the incident field and reduces the net field within the shell. In the induced current generation process, some of the energy of the incident magnetic field is dissipated as heat, which also reduces the internal field.

For maximum shielding effectiveness, it is essential that:

1. The shielding shall form electrically continuous loops at right angles to the H-field direction. But, since the H-field associated with EMP may appear from any direction, the shield should be electrically continuous in all directions.
2. Since magnetic flux may be more concentrated near shield surfaces or openings, attenuation variations with respect to location within shielded volumes should be considered. See Sections 5.3.3.3, 5.3.4.3, 5.3.5.3, and 5.3.7.3.
3. Since discrete discontinuities such as loose joints or breaks in conduits and metal service piping can produce severe flux concentrations and high induced voltages, care must be exercised in joint construction to insure continuity for shielding.

5.3.1.3 "Overall" versus "Local" Shielding Practices

Protection techniques applying to EMP shielding for buildings involve

the use of solid metal panels, reinforcing steel bars (rebars), or welded wire fabric in the ceiling, walls, and flooring of the building to be shielded. This practice is defined as "overall" shielding.

"Local" shielding is defined as the use of the above shielding materials, or metal screen cloth, for certain rooms or parts of the building containing several rooms. Cabinet-type enclosures are also contained in this classification. "Local" shielding is also extended to apply to certain components and metal conduits to shield wiring.

"Overall" shielding can be used to provide all the attenuation needed for the most susceptible piece of equipment or it may be used to provide only a portion of the required attenuation, in which case the additional attenuation needed would be provided by "local" shielding.

Table 5.1 compares these basic approaches to shielding and cites the advantages and disadvantages of each practice.

5.3.2 EMP Shielding for Wiring in Conduits and Precautions for Metal Utility Piping

Power cables, open buses, and other wiring in conduits within the power building and conduit runs between the power plant, MSCB, or DCCB and site facilities are susceptible to EMP fields, especially if they have extensive exposure. To attenuate the induced voltages developed by such fields between conductors and from conductors to conduit, all electrical conductors shall be completely contained within conduit and all metal utility piping shall be electrically continuous except as specifically allowed in other sections of these protective measures.

5.3.2.1 Requirements for Conduits in Shielding Applications and for Metal Utility Piping

For conduits to be effective as EMP shields for enclosed conductors and for metal utility piping to function safely, certain design requirements applicable to conduits and piping have been incorporated in the protective measures. These include the following:

1. All metal utility piping shall be electrically continuous; also all

TABLE 5.1

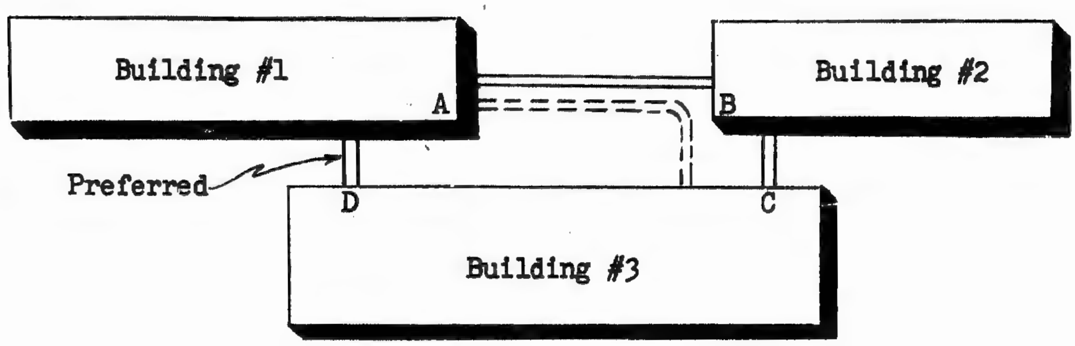
COMPARISON OF SHIELDING APPROACHES

Advantages	Disadvantages
"Overall" Shielding of Buildings	
1. Building shield can be made to provide all the required shielding, or may be made to provide the majority of the required shielding.	1. Complex design and fabrication requirements for a building that provides complete shielding attenuation.
2. Location of equipment can be dictated by functional requirements.	2. Monitoring of shielding effectness and shielding maintenance are difficult.
3. Standard "off-the-shelf" components may be used.	
"Local" Shielding of Rooms	
1. Access and air openings are small and easily fabricated and maintained.	1. All susceptible equipment must be placed in an appropriately controlled shielded area. Total building becomes less flexible with regard to equipment location. Expansion and equipment relocation may be difficult.
2. Shielding attenuations are readily monitored and maintained.	
3. Individual equipment is easily available for maintenance and trouble-shooting.	
"Local" Shielding of Components	
1. Individual shielding attenuations are easily monitored and maintained.	1. "Off-the-shelf" components may require modification to operate satisfactorily or to attenuate EMP fields sufficiently.
2. Component housings as supplied may provide partial shielding, so that rebar or wire fabric shielding of the building or room can provide the remaining attenuation if it is required.	2. Each purchased component and associated wiring may require proof of performance in simulated EMP fields.

conduit runs shall be electrically continuous so that conductors are never directly exposed to an EMP field environment. (Special problems associated with flexible conduit joints are covered in Section 5.3.2.2.)

2. All conduit and metal utility piping terminations shall be made at buildings or metal enclosures as prescribed in Section 5.3.2.2.
3. All conduits exposed to an EMP field environment shall be assembled under rigid inspection to eliminate any construction faults which would produce openings or leakage paths for magnetic flux or produce high resistance joints.
4. Rigid steel conduit of two-inch trade size or larger shall be used outside any building. Rigid steel conduit one-inch trade size or larger should be used inside buildings. Conduit couplings should be threaded. If joints are not continuously welded after threading, threads shall be coated with an electrically conductive sealant before threading. Conduit bends can be either factory made or field made, but must be radiused in accordance with code requirements. Condulets should be used only where the protective measures specifically permit. Charts covering the effects of conduit joints and bends are presented in Section 5.3.2.3. The use of aluminum conduit or electrical metallic tubing (EMT) and fittings of one-inch trade size or larger is generally restricted. Sections 2.2 and 2.3 list these restrictions.
5. Conduits and metal piping entering or leaving a building may penetrate the building in many areas. However, conduits and metal utility piping between buildings should be run in a group. (Section 5.3.2.3)
6. The length of metal utility piping and conduit runs and the number of loops in runs shall be kept to a minimum. Where construction and site requirements permit, it is preferable to have short piping

and conduit runs rather than to eliminate the loops by lengthening the runs. This can be illustrated simply by considering the plot plan of three buildings (#1, #2, and #3) which must be interconnected by conduits or piping.



A loop (ABCDA) is formed by running the piping or conduit from Building #3 to Building #1 (solid lines), but this arrangement is preferred to the alternative of longer runs indicated by the dashed line from Building #3 to Building #1 via Building #2 that would eliminate the loop. Either practice is acceptable, however, within the limitations given in Section 3.0.

Several important design requirements relating to metal utility piping have also been prescribed in the protective measures. Specific requirements pertaining to the installation of utility piping are as follows:

1. All metal utility piping shall be free of high resistance sections or joints throughout its length. This requirement would be met by following normal construction practices.
2. If construction considerations dictate the use of non-metal pipe sections between metal pipe sections or insulating joints, the non-metal section(s) or joint(s) shall be bridged by bonds, as covered in Section 5.2.3.11.

5.3.2.2 Metal Utility Piping and Conduit Penetrations at Buildings and Enclosures

Conduit runs and metal utility piping between buildings must be properly grounded to prevent the entry of currents into buildings and to maintain the shielding effectiveness of the structures. For these reasons some specific techniques for constructing piping and conduit penetrations at buildings have been developed.

The protective recommendations presented in Sections 2.0 and 3.0 are premised upon conduit and piping penetrations constructed to conform with the following requirements:

1. Conduits and metal utility piping penetrating an outside unshielded wall or building shielded by rebars or welded wire fabric at or near the counterpoise level shall be connected directly to the counterpoise mat as shown in Figure 5.10. If such piping and conduit penetrations are at a level not greater than 1/2 the total building height, the arrangement using grounding plates shown in Figure 5.11 shall be used. For cases which may warrant flexibility between building and conduit, a corrugated flexible tube (bellows) may be inserted into the conduit system after the grounding plates. The bellows shall have either a flexible braid covering (preferred) or three #1/0 AWG jumpers connected across the bellows.
2. For conduit and metal piping which penetrate outside unshielded walls or rebar shielded walls at levels greater than 1/2 the total building height, the penetration arrangement using grounding plates and a wire mesh as shown in Figure 5.12 shall be used. Wire meshes from widely spaced conduits or conduit groups can be connected to a common wire mesh which traverses the top of the building. Several typical wire mesh installations showing methods of wire mesh connection are shown in Figure 5.13. Note that Item D in Figure 5.13 shows that when conduit penetrations are below 1/2 total building height, no wire mesh is necessary.

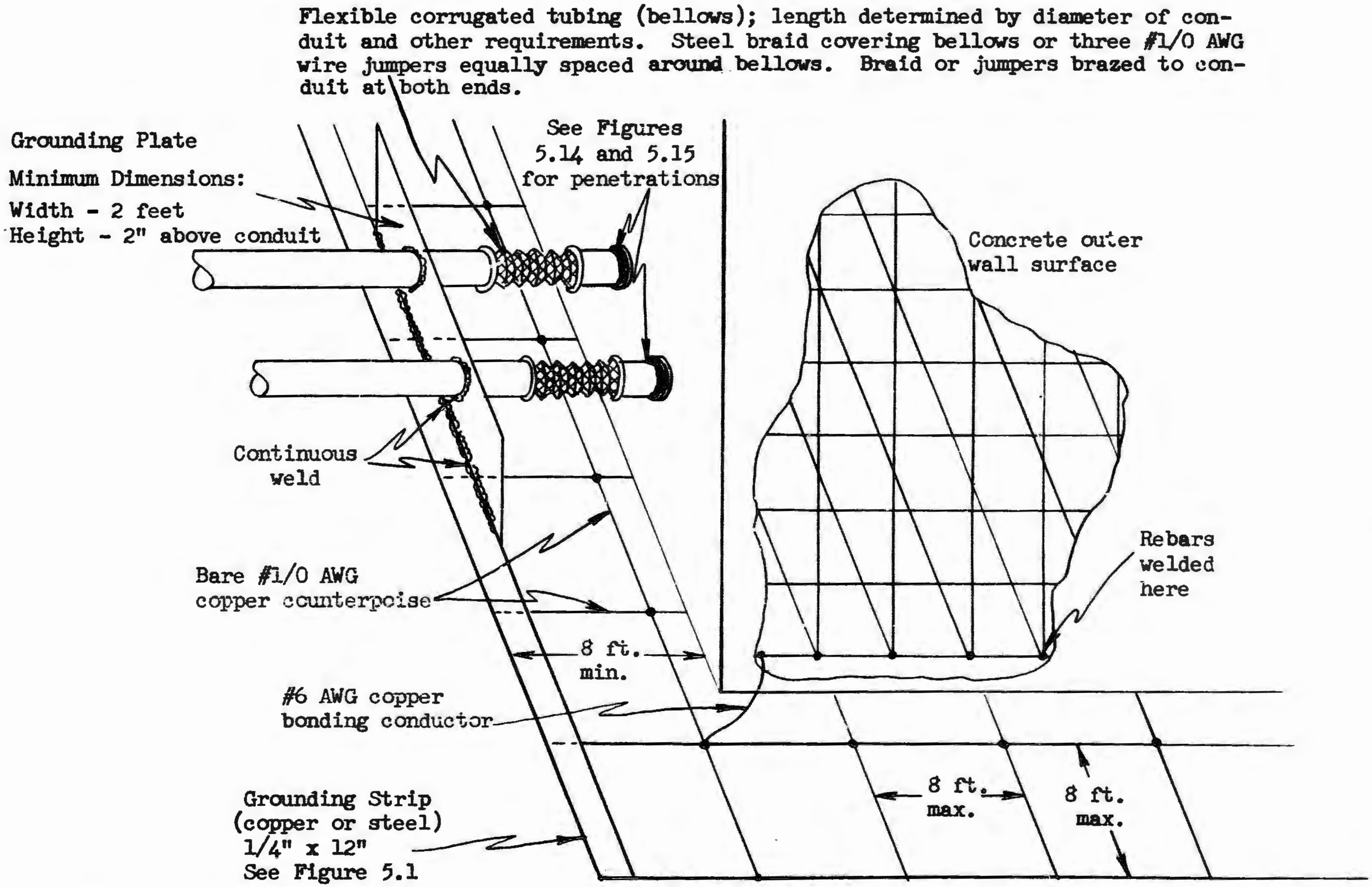


FIGURE 5.10 Conduit or Pipe Ground Connections at Counterpoise for Penetrations of an Outside Unshielded Wall or Wall Shielded with Rebars or Welded Wire Fabric Shielding at Counterpoise Elevation. Does not apply to Overall Metal Shielded Buildings.

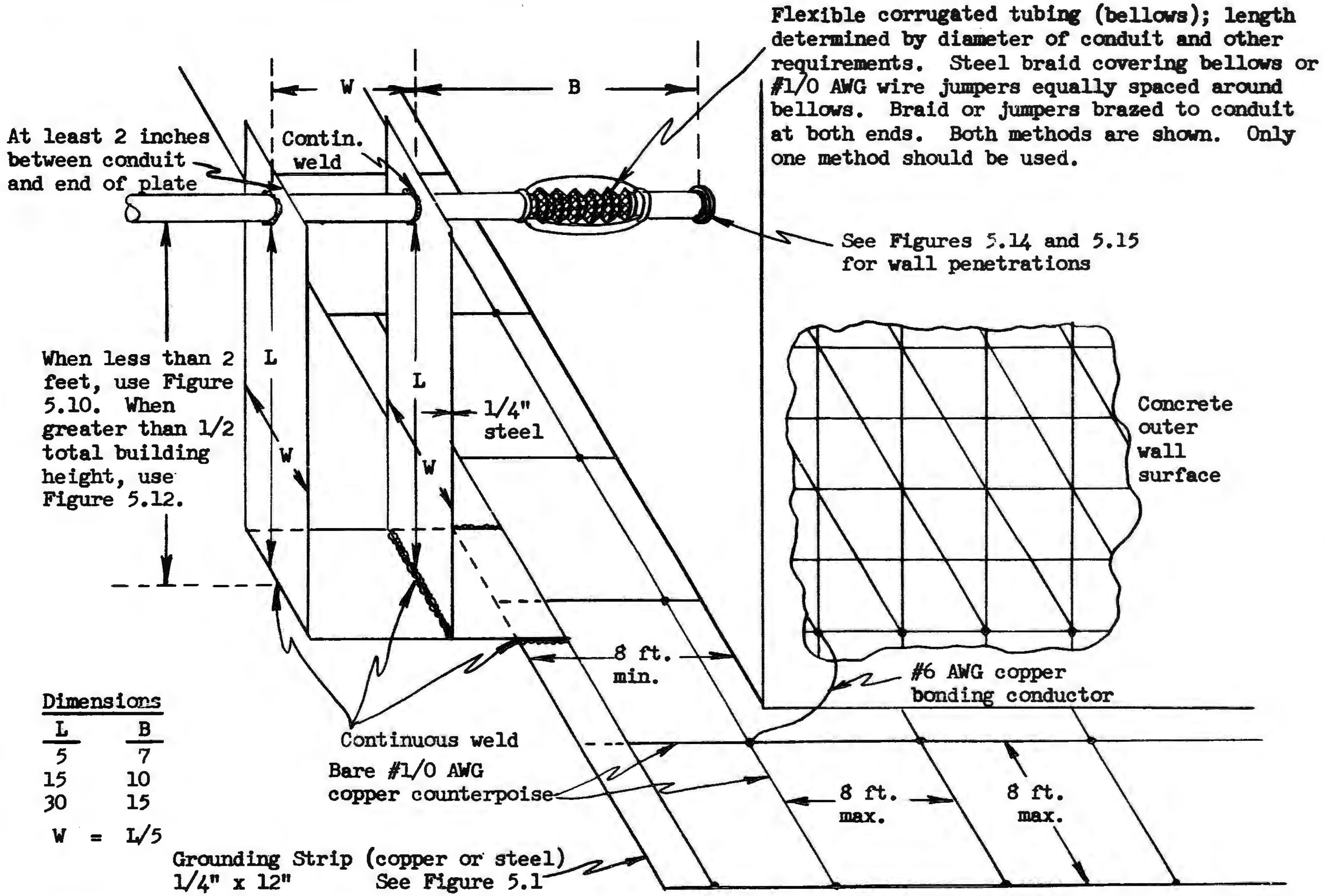


FIGURE 5.11 Conduit or Pipe Ground Connections at Counterpoise for Penetrations at an Unshielded Wall or Wall Shielded with Rebars or Welded Wire Fabric at Elevations Above the Counterpoise. Does not apply for overall metal shielded buildings and conduit penetration heights greater than 1/2 the total building height.

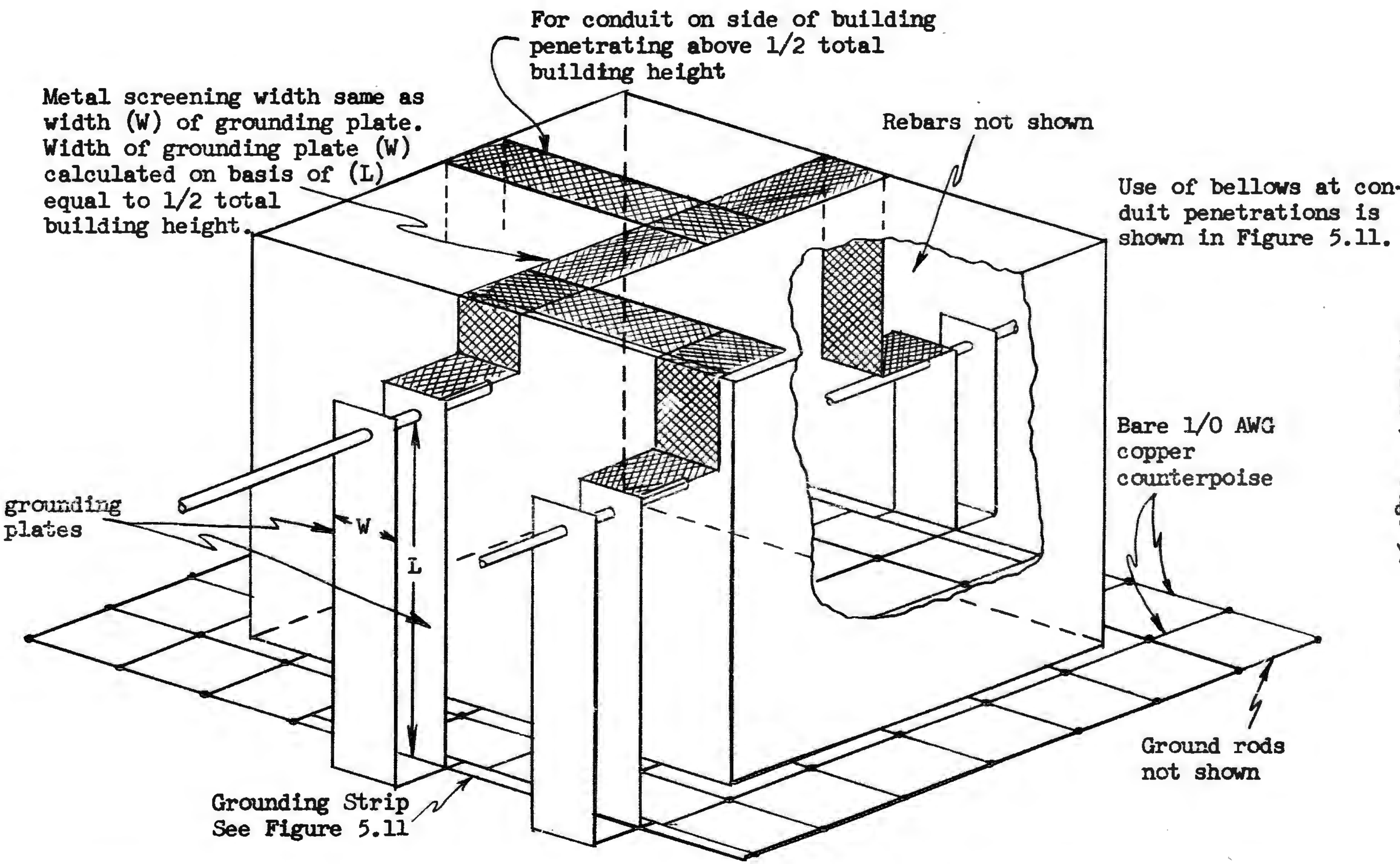


FIGURE 5.12 Conduit or Pipe Ground Connections at Counterpoise for Penetrations of an Outside Unshielded Wall or Wall Shielded with Rebars or Welded Wire Fabric Shielding above Counterpoise Elevation. Does not apply to overall metal shielded buildings and conduit penetration heights less than 1/2 the total building height.

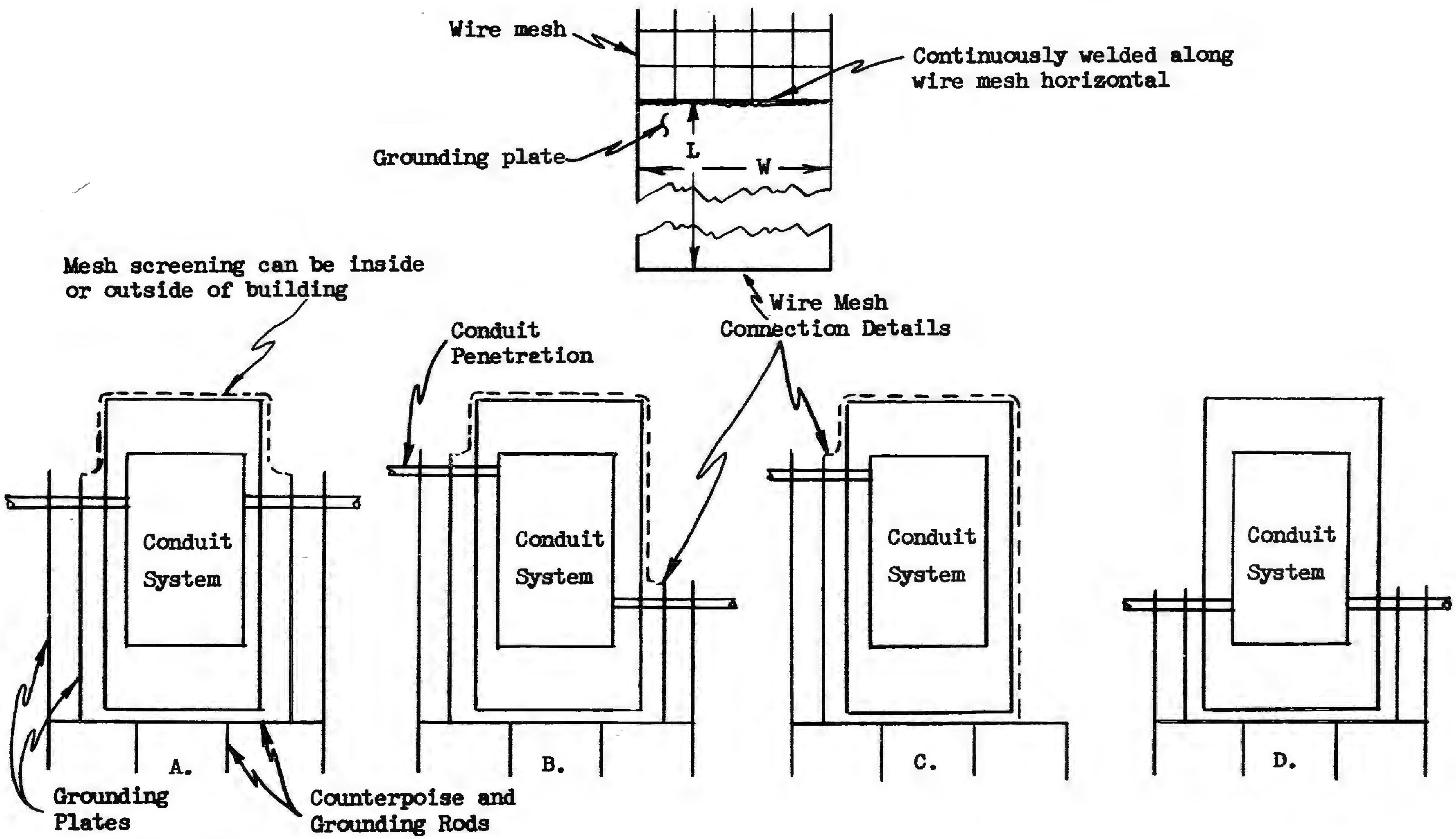


FIGURE 5.13 Typical Installations for Conduit Penetrations at Heights Greater than 1/2 Total Building Height showing Methods of Wire Screen Connection. Does not apply to overall metal shielded buildings.

3. For conduit and piping penetrations, the conduit or piping shall be continuous in passing through the wall. Where flexible conduit penetrations are required, the method shown in Figure 5.14 may be used.
4. Metal utility piping and conduits penetrating an outside wall shielded with solid metal plate shall be bonded to the metal plate as shown in Figure 5.15.
5. Metal utility piping and conduits penetrating an inside wall with rebar or welded wire shielding shall be bonded to the internal grounding ring as shown in Figure 5.16(A & B). If the wall shielding consists of solid metal plate, the conduit should be welded directly to the shielding at the point of penetrations, as shown in Figure 5.16C. Wave guides shall not be used.
6. Cable trays, when their use is permitted, shall penetrate a solid metal sheet wall as shown in Figure 5.17. An unshielded area penetration is also shown.
7. Conduits terminating at a metal equipment enclosure shall be welded or attached by locknuts and bushings to the enclosure panel at the point of penetration and the enclosure shall be bonded to the internal grounding rings as shown in Figure 5.18.
8. Non-metal piping penetrations into metal plate shielded areas shall be through wave guides which maintain the shielding integrity of the shielded volume.
9. Bus enclosure penetrations into shielded areas shall maintain the shielding integrity of the shielded volume. If wall shielding consists of metal plate, the bus enclosure should be continuously welded to the metal plate at the point of penetration. If a bus enclosure penetrates an unshielded area, the bus enclosure must be totally enclosed and electrically continuous to its terminus and maintain its shielding integrity.

There are no special requirements for rigid conduit or metal piping penetrations of inside, unshielded walls other than the basic requirement

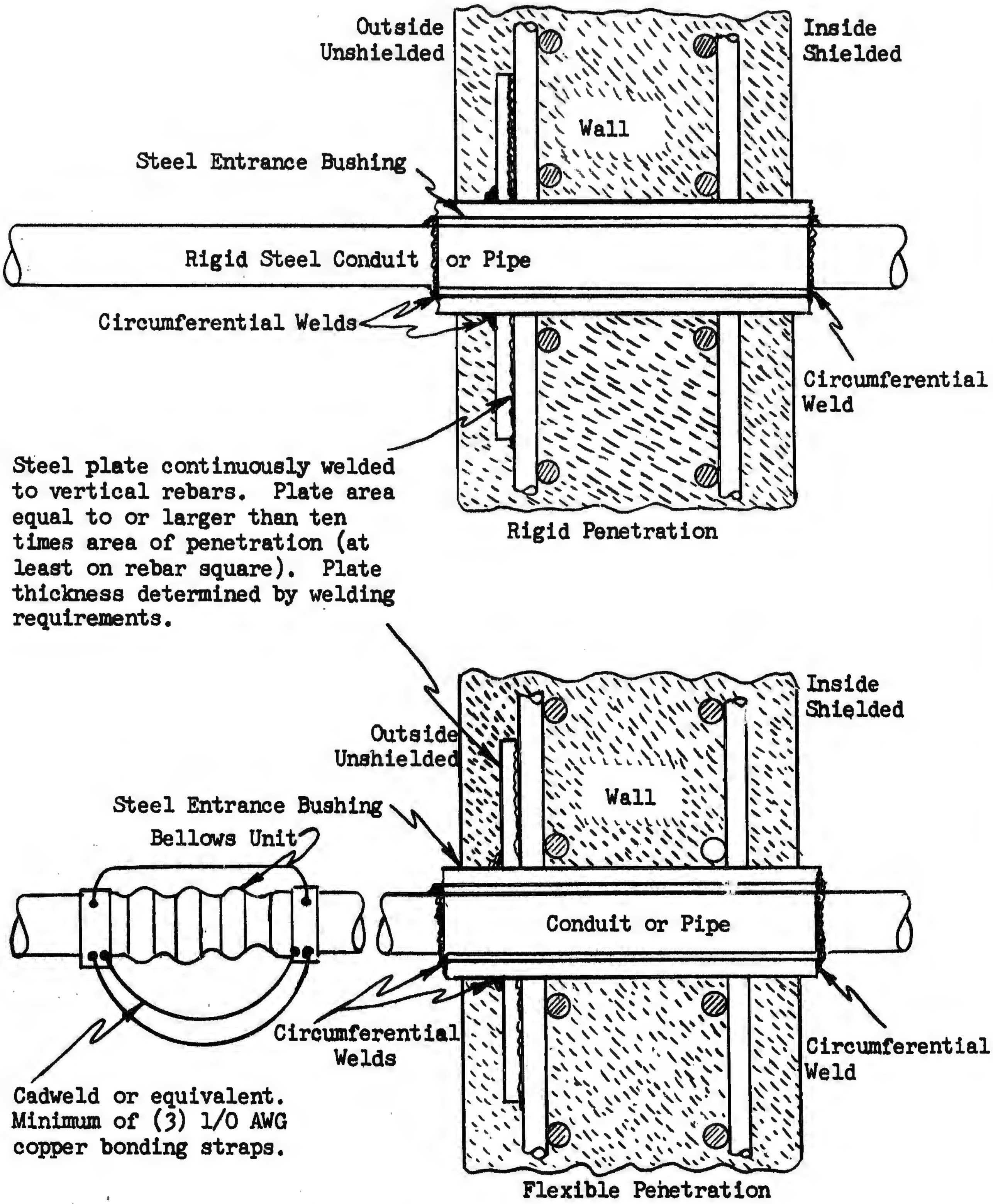
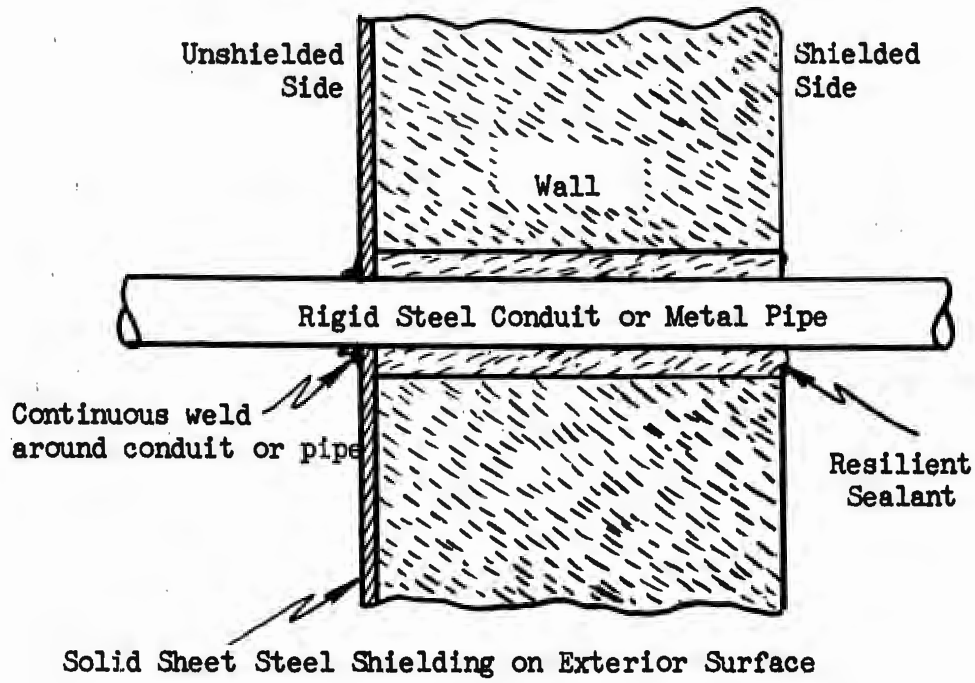


FIGURE 5.14 Outside Wall Penetrations with Double-Course Rebar Construction



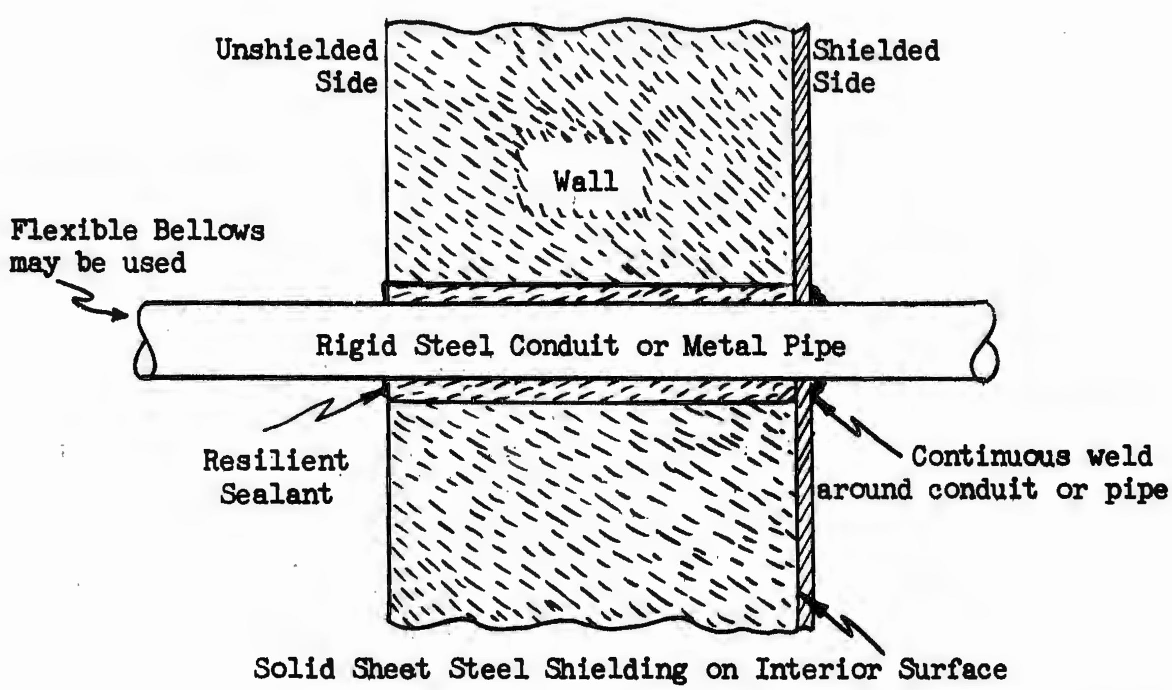
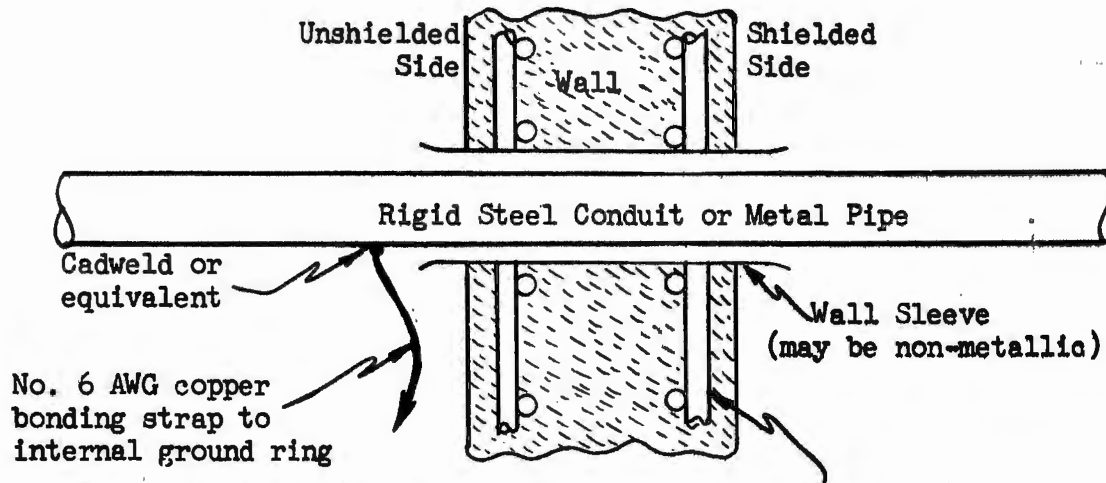
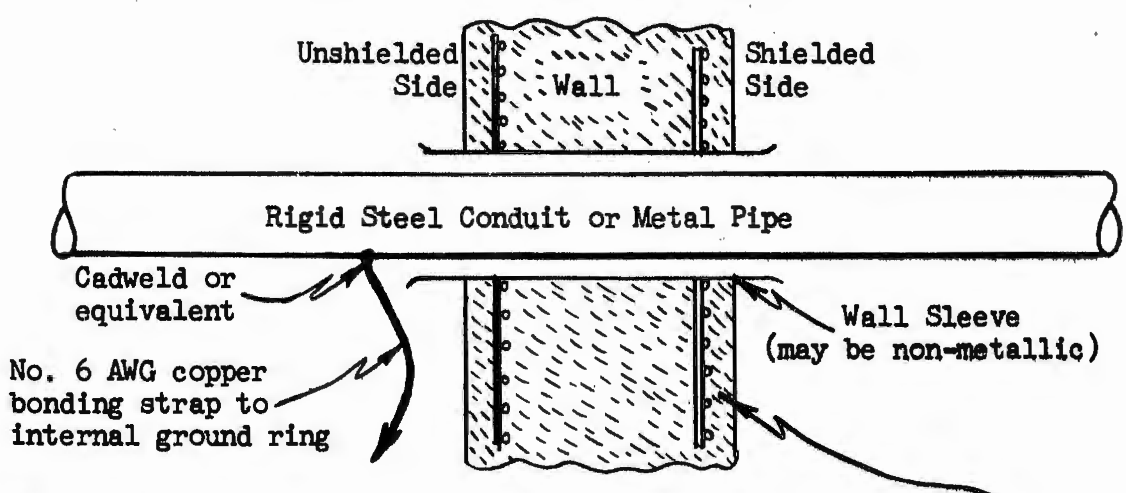


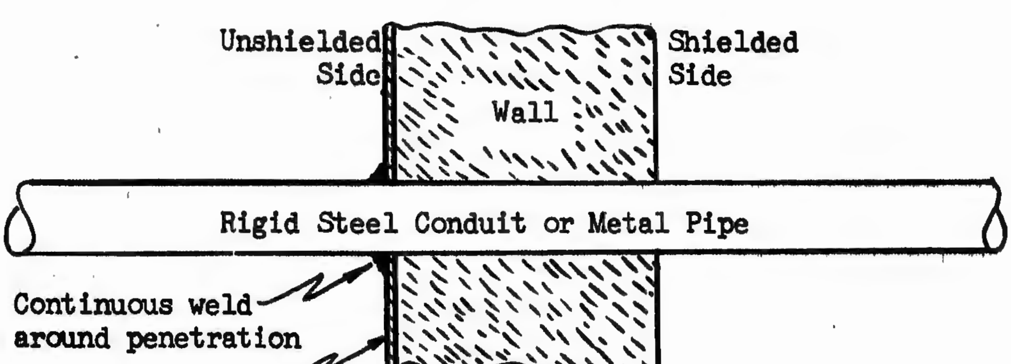
FIGURE 5.15 Outside Wall Penetrations with Solid Sheet Steel Shielding



A. Rebar Shielding (double-course construction)

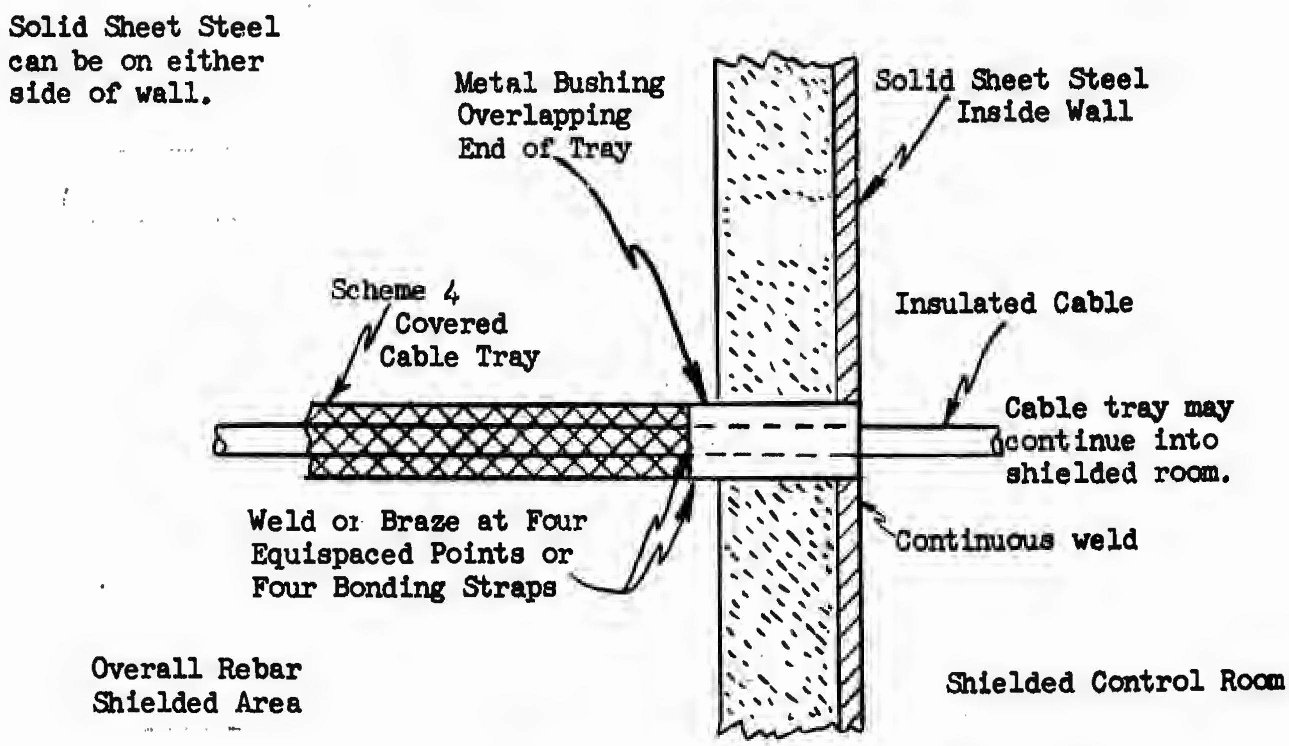


B. Welded Wire Fabric Shielding (double-course construction)

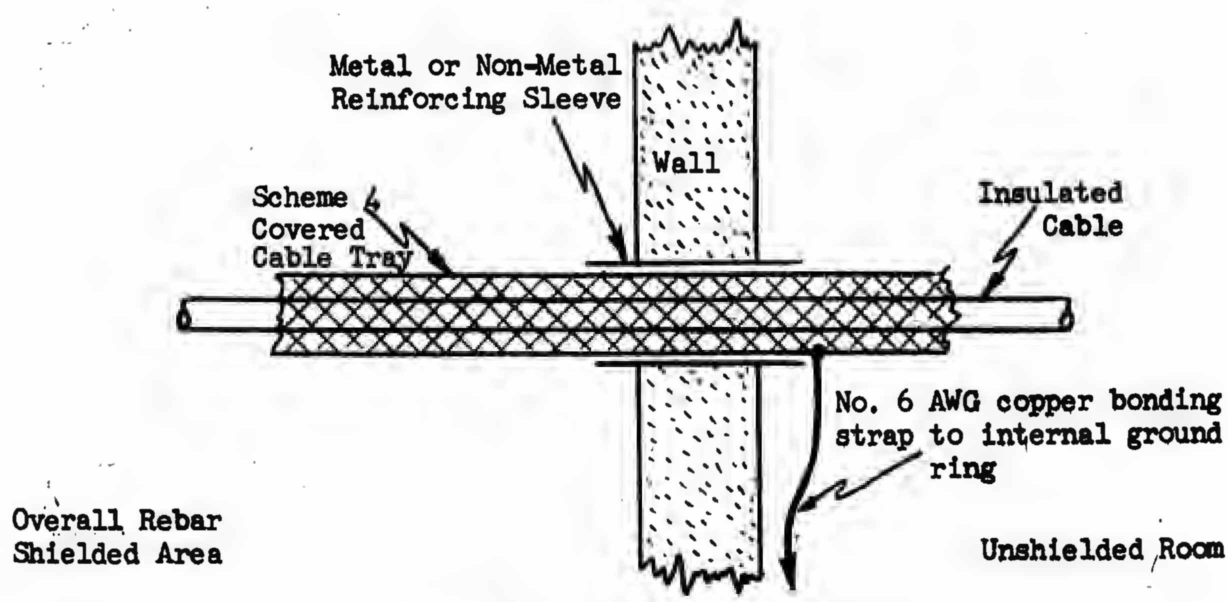


C. Solid Sheet Steel (or Plate) Shielding

FIGURE 5.16 Inside Wall Penetrations with Rebar, Welded Wire Fabric or Solid Sheet Steel (or plate) Shielding



Penetration into Shielded Area



Penetration into Unshielded Area

FIGURE 5.17 Inside Wall Cable Tray Penetrations

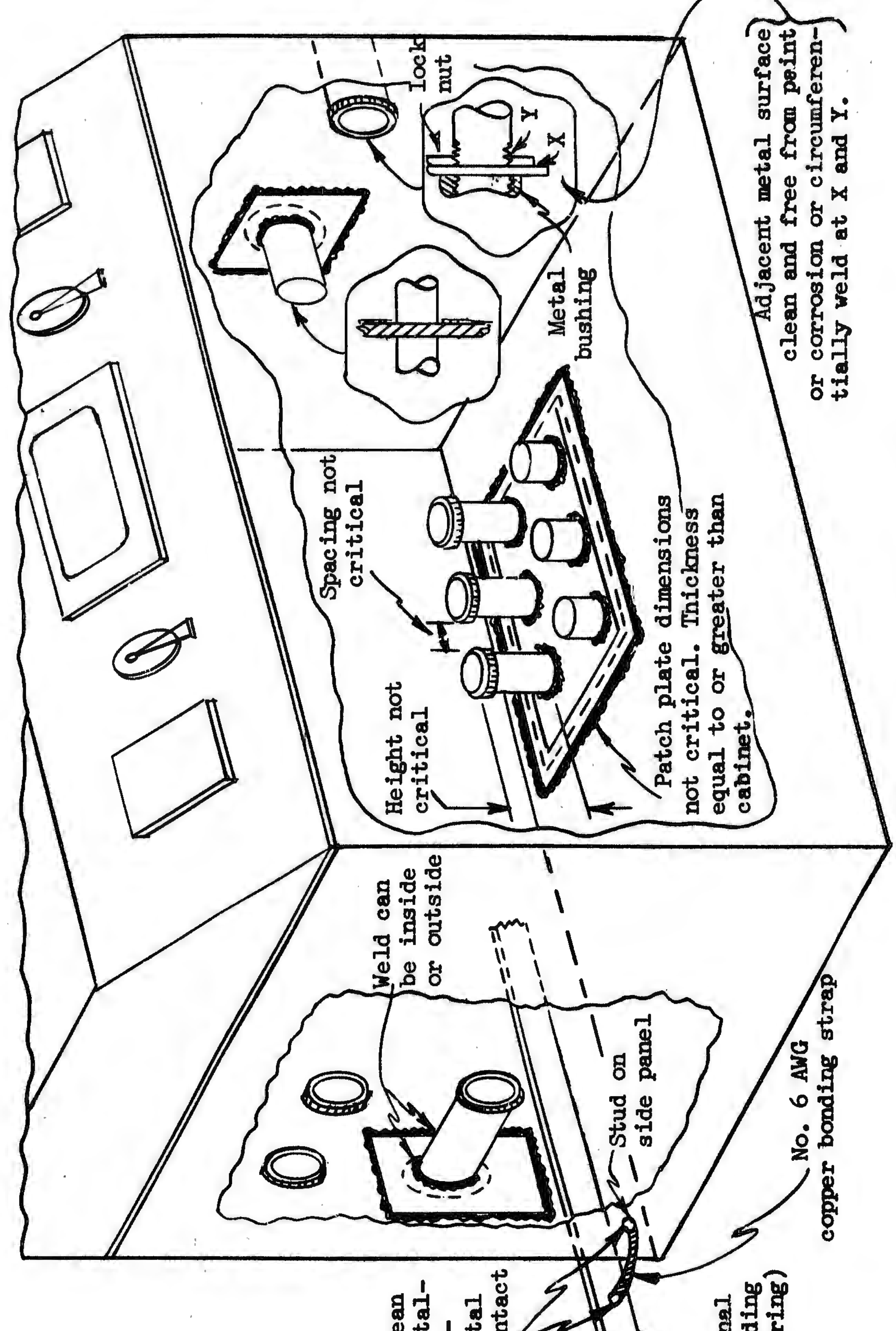


FIGURE 5.18 Conduit Terminations at Equipment Cabinets (Does not apply to shielded control room.)

that the shielding integrity of conduits be maintained.

5.3.2.3 Relationships between Factors Affecting the Susceptibility of Conduit Wiring to EMP Fields and Design Requirements for Conduits and Metal Utility Piping

Techniques of shielding all electrical circuits by enclosing them in conduits were discussed in Sections 5.3.2.1 and 5.3.2.2. The practices required in these sections have been specified because conduit wiring is susceptible to EMP fields.

The purpose of this section is to list and relate factors affecting the susceptibility of conductors in conduits with the design features specified. The effect of these factors on the electromagnetic response of the electrical system is discussed in Section 4.0.

Voltages induced on conductors within conduit have complex wave forms and depend upon a number of factors, including:

1. The current through the conduit produced by the H-field environment. This creates a voltage drop through the resistance of the conduit, which can be coupled into contained conductors.
2. The type of conduit material used. Higher magnitude induced voltages tend to appear on low permeability conduits, such as those made of aluminum than those of high permeability, such as steel.
3. The diameter (trade size) and wall thickness of the conduit. There is less coupling of induced voltages into conductors within large diameter conduits than into small ones; also, induced conductor voltages vary approximately in inverse proportion to the square of the conduit wall thickness.
4. The number and kind of bends influence both magnitude and wave shape of induced voltages on conductors. These induced voltages are directly proportional to the number of bends (Figure 5.19). Higher conductor voltages are induced in severe, short-radius bends than in gradual ones. This, in part, is the basis for general avoidance of condulets in conduit assembly. Another reason

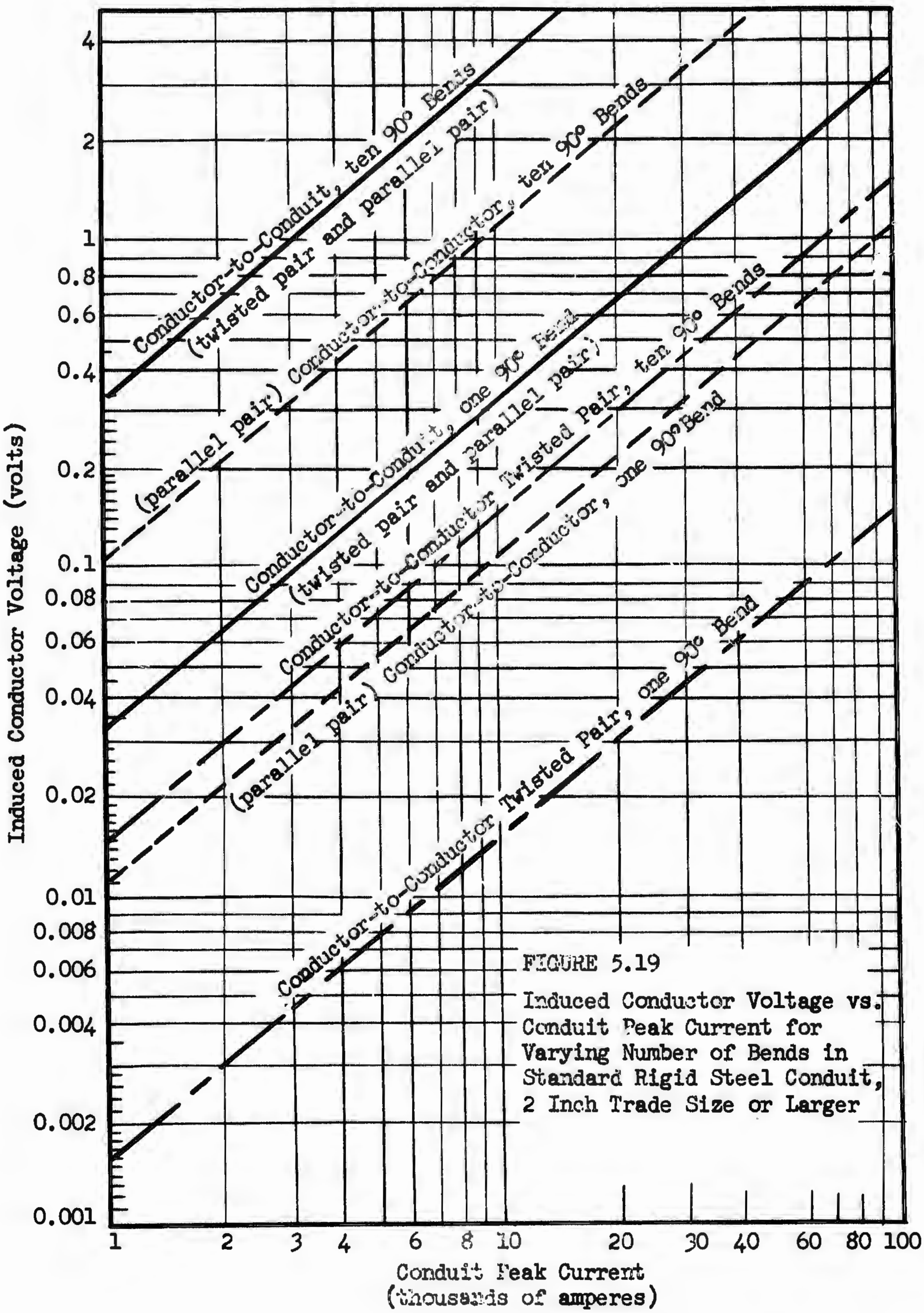


FIGURE 5.19

Induced Conductor Voltage vs. Conduit Peak Current for Varying Number of Bends in Standard Rigid Steel Conduit, 2 Inch Trade Size or Larger

is that condulet covers may be accidentally removed or omitted, resulting in extremely high flux leakage into the conduit with consequent increases of voltages induced on the wiring.

5. The number of conduit couplings. Figure 5.20 shows that induced conductor voltages are directly proportional to the number of couplings in a conduit run, assuming that all the joints are constructed to a high standard of workmanship. Even one poorly made or loose joint could enormously increase these induced voltages. This supports the requirement of electrically-conducting sealants on threaded couplings or continuous welds at threaded couplings.
6. The length of conduit runs. Voltages induced on conductors in conduits are directly proportional to conduit length, as indicated in Figure 5.19. This dictates the need of careful design to minimize the length of conduit runs.
7. The actual position and arrangement of conduits grouped together in ducts or trenches between buildings. Experimental and analytical results of several conduit grouping arrangements have indicated that the H-field induced current will divide between the individual conduits within the group with the higher current being carried by the outermost conduits in the group. This suggests that, wherever possible, the power wiring should be run in the outermost conduits in a group and signal wiring should be run in the innermost conduits.

When conduits are run in groups, the resulting current division, in effect, reduces the induced voltage on the wiring within these conduits. The induced voltage from wiring within a conduit for given conduit currents as determined by the nomograph, Figure 4.2, can be obtained from Figures 5.19 and 5.21. To determine the value of current to use for Figures 5.19 and 5.21 when conduits are run in a group, refer to Figure 5.22. The multiplying factors given in

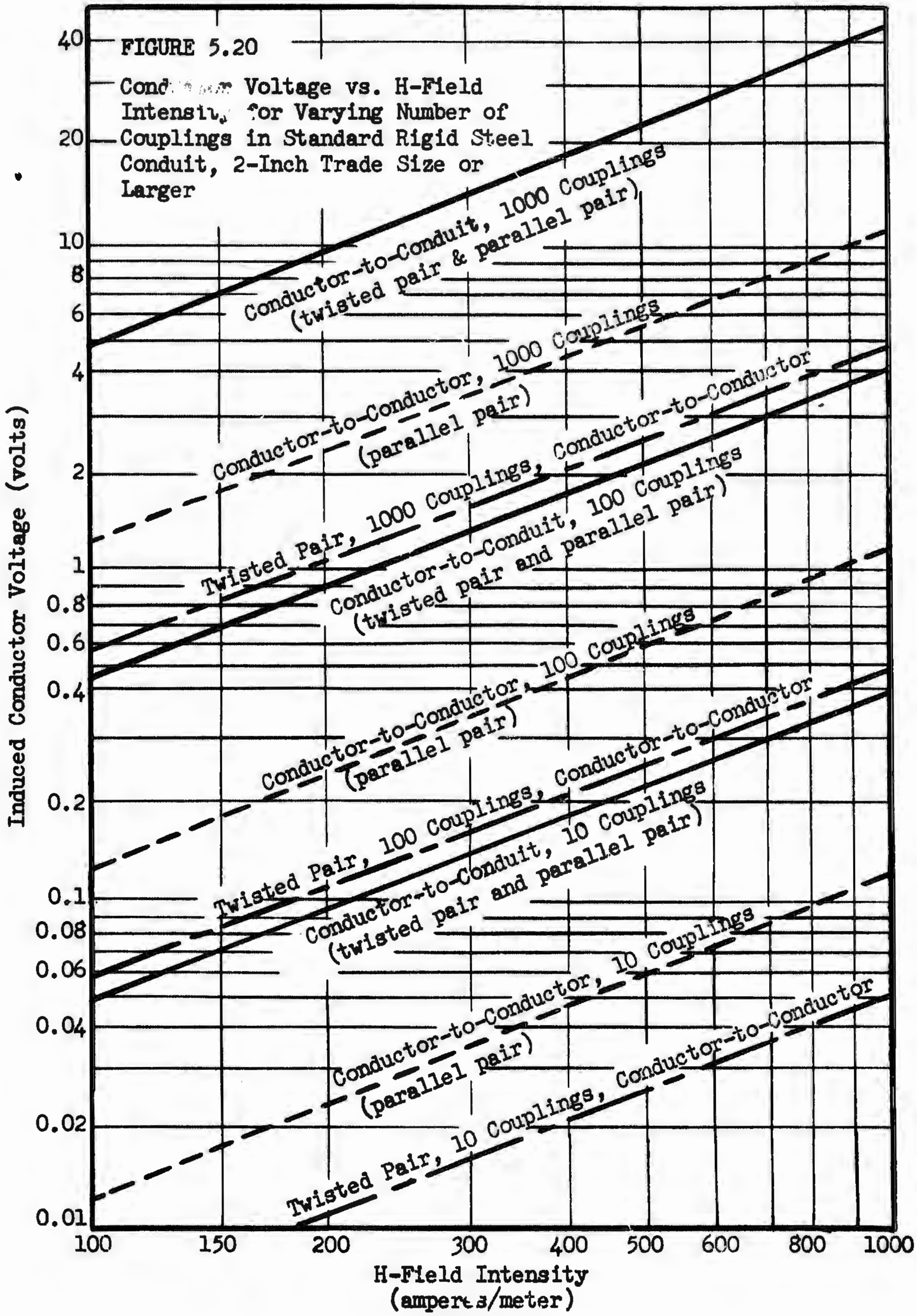


FIGURE 5.20
Cond... Voltage vs. H-Field Intensity for Varying Number of Couplings in Standard Rigid Steel Conduit, 2-Inch Trade Size or Larger
Conductor-to-Conduit, 1000 Couplings (twisted pair & parallel pair)
Conductor-to-Conductor, 1000 Couplings (parallel pair)
Twisted Pair, 1000 Couplings, Conductor-to-Conductor
Conductor-to-Conduit, 100 Couplings (twisted pair and parallel pair)
Conductor-to-Conductor, 100 Couplings (parallel pair)
Twisted Pair, 100 Couplings, Conductor-to-Conductor
Conductor-to-Conduit, 10 Couplings (twisted pair and parallel pair)
Conductor-to-Conductor, 10 Couplings (parallel pair)
Twisted Pair, 10 Couplings, Conductor-to-Conductor
Induced Conductor Voltage (volts)
40
20
10
8
6
4
2
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
100
150
200
300
400
500
600
800
1000
H-Field Intensity
(amperes/meter)

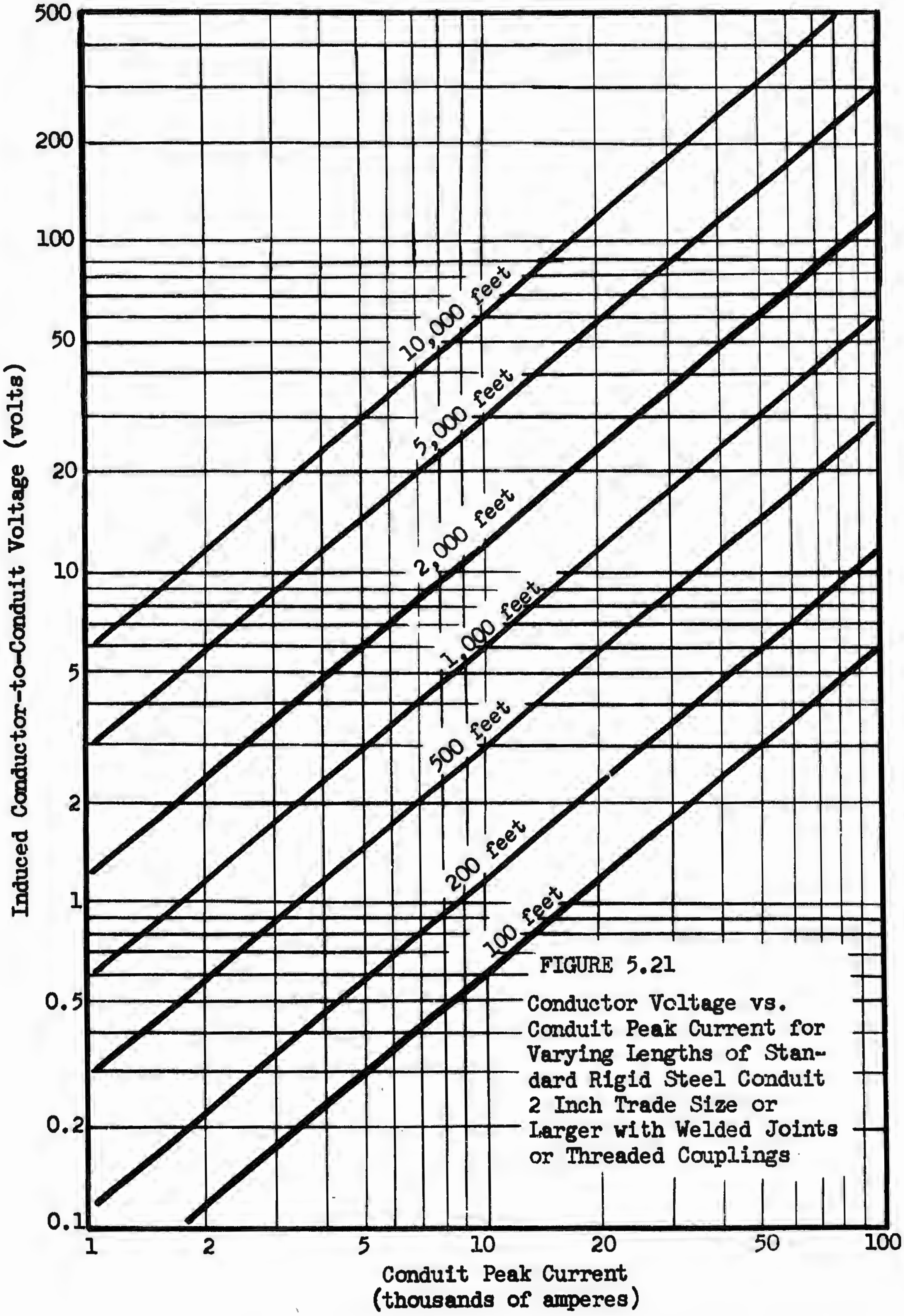
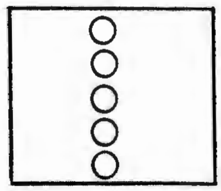


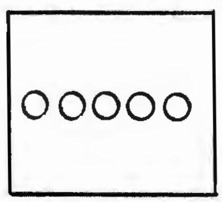
FIGURE 5.21

Conductor Voltage vs. Conduit Peak Current for Varying Lengths of Standard Rigid Steel Conduit 2 Inch Trade Size or Larger with Welded Joints or Threaded Couplings



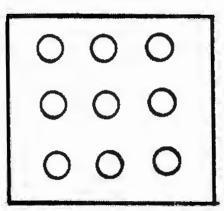
For a vertical conduit arrangement, the induced current on conduits, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by $1/\sqrt{N_V}$, where N_V is the number of conduits in the trench or duct.

A. Vertical Arrangement of Conduits in a Duct or Buried in a Trench



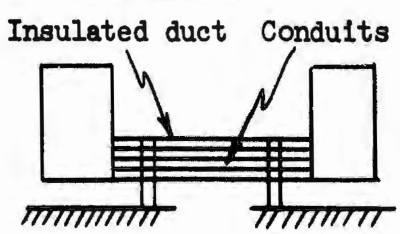
For a horizontal arrangement, the induced current on conduits, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by $1/\sqrt{N_H}$, where N_H is the number of conduits in the trench.

B. Horizontal Arrangement of Conduits in a Duct or Buried in a Trench



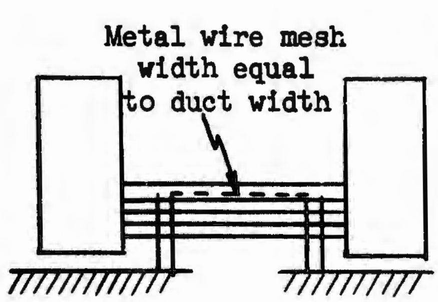
For a vertical and horizontal arrangement, the induced current on conduits, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by $1/\sqrt{N_V} \times 1/\sqrt{N_H}$, where N_V and N_H are as in A and B above.

C. Vertical and Horizontal Arrangement of Conduits in a Duct or Buried in a Trench



When conduits are placed in insulated ducts, the induced conduit current, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by 1/1.25 in addition to the factor given above relating to conduit arrangement.

D. Conduits in Insulated Duct between Buildings



When a wire mesh is placed above conduits and connected to the grounding plate at both ends of the duct, the induced current on conduit, as determined by the nomograph, Figure 4.2, and used for conduit wiring response calculations (Section 4), must be multiplied by the following factors in addition to those given above relating to conduit arrangement.
For wire mesh 2.5 feet above conduit multiply by 1/2.
For wire mesh 4.0 feet above conduit multiply by 1/3.

E. Conduit Ducts with Metal Wire Mesh Placed above Conduits in Duct

FIGURE 5.22 Physical Conduit Arrangements Affecting the Induced Current on Conduits and the Resulting Induced Voltage on Wiring

Figure 5.22 are conservative. An example of how Figure 5.22 is used in electrical system response calculations is given in Section 4.5.3.

8. The types of conductors within the conduit. Because of the greater area presented to EMP flux leaking into the conduit, voltages induced on parallel pairs will generally be higher than on twisted pairs (Figures 5.19 and 5.20). Cables constructed with wound or braided shields within conduit are very effective in reducing the induced voltages, provided such shields are properly grounded.
9. The actual position of conductors within conduits. This also affects the induced voltages, but this factor is beyond control by design; only random positions can be assumed.

Metal utility piping, if continuous and routed near conduits, will afford some additional shielding for wiring in the conduits by diverting EMP field-induced currents away from the conduits.

It is essential that all metal piping runs have good electrical conductivity. Tests indicate that high voltages will be induced at points of discontinuity in large piping loops. (See Section 4.2.2.) This is the basis for applying bonds across all insulated sections and joints as required in Sections 5.2.2.4 and 5.3.2.1.

5.3.3 EMP Shielding for Structures and Equipment Rooms by Solid Metal Plate

5.3.3.1 Fields of Attenuation

Section 5.3.3 covers metal plate shielding for structures and equipment rooms, but does not include shielding for metal equipment enclosures and cabinets. These are treated in Section 5.3.7.

Solid steel or aluminum plates, properly designed and installed, will provide adequate EMP shielding for structures and equipment rooms of all sizes. Tests indicate that the shielding effectiveness or attenuation ability of a completely sealed structure or equipment room is more dependent upon metal plate thickness, resistivity, and permeability than upon dimensions.

Since openings, proximity effects, penetrations, and inadequate construction practices degrade shielding performance, the following subsections will cover specific construction practices and the methods of evaluating the attenuation afforded by this type of shielding.

5.3.3.2 Construction Practices for Solid Metal Plate Shielding

To minimize shielding degradation effects required construction practices are as follows:

1. Metal panels shall completely enclose the building or equipment room to be shielded, except for necessary openings and penetrations; details of shielding these are covered in Requirement 4., below.
2. All metal panels used for shielding shall have continuously welded or brazed seams.
3. When metal shielding plates are applied on the inside of a building or an equipment room, each junction between wall, ceiling, and floor surfaces shall be welded or brazed as in Requirement 2., above; also, to achieve maximum attenuation in the corner region each junction can be covered with a 1.5 foot wide strip (fillet plate) of the metal used for shielding. This fillet shall be attached by continuous seam welding or brazing, as shown in Figure 5.23. For situations where sensitive equipment will not be located closer than six inches from a wall shield, fillet plates need not be used.
4. The number of openings and penetrations into a shielded building or equipment room should, by careful design, be kept at a minimum. Large access openings, which would rarely be used after the initial installation of large equipment in the building or room, shall be provided with removable panels, welded or brazed closed after use. Smaller access openings, such as personnel doorways, shall be shielded by wave guide tunnels or double door vestibules. Design proportions of such wave guides depend upon the amount of attenuation

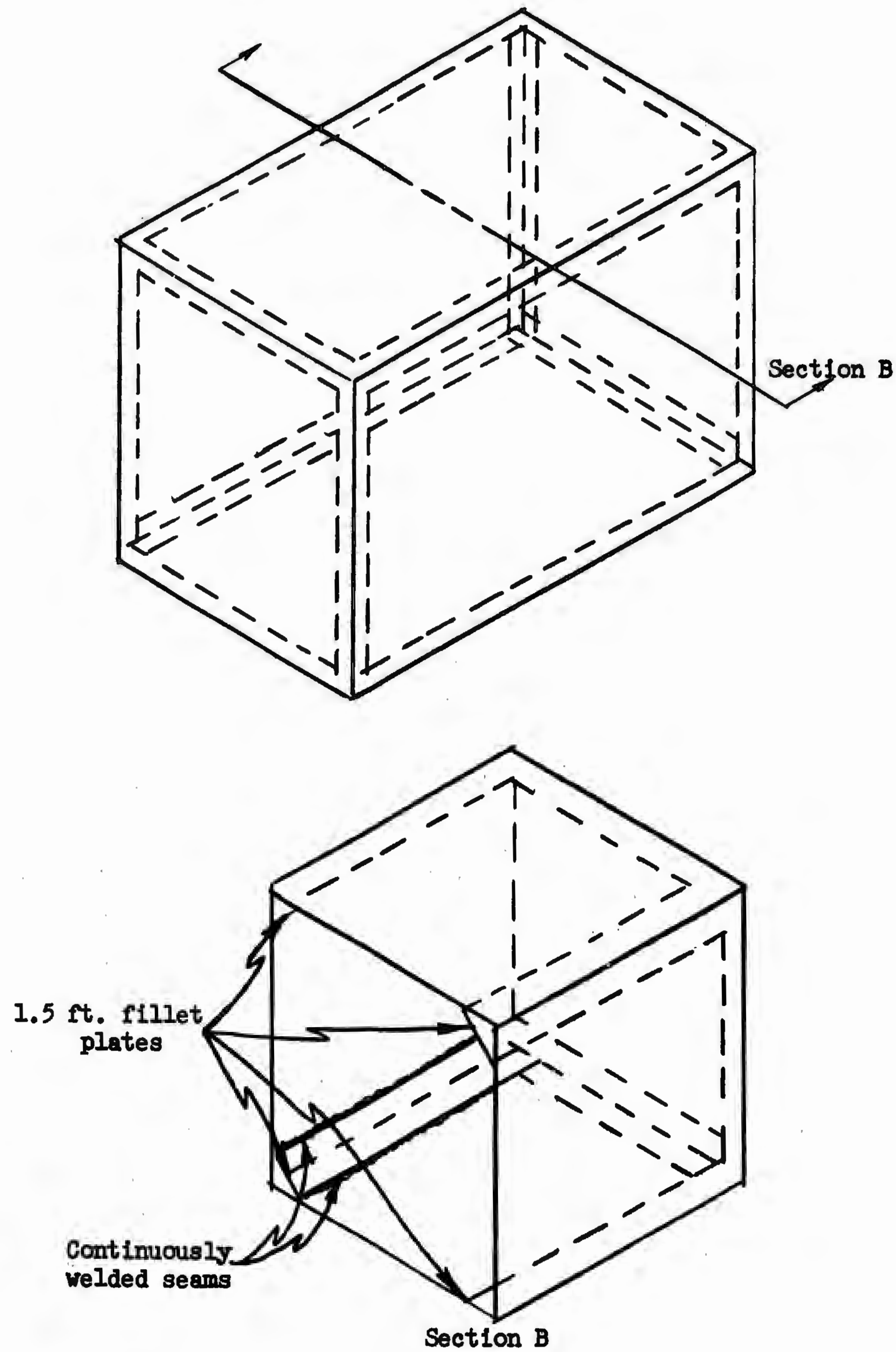


FIGURE 5.23 Construction Details of Metal Plate Fillets for Rooms and Buildings

afforded by the building or room shielding and can be determined by the techniques given in Section 5.3.3.3. The vestibule type of construction requires doors to be fitted with contact fingers or spring strips which maintain good electrical contacts between the edges of the door and its jamb.

5. Electrical conduits and/or metal utility piping entering from outside and penetrating metal plate shielding shall be continuously welded or brazed to the building or room shielding at the point of entrance, as shown in Figure 5.15.
6. Electrical conduits and/or metal utility piping penetrating an inside wall with solid metal plate shielding shall be continuously welded or brazed to the shielding at the point of penetration, as shown in Figure 5.16C.

5.3.3.3 Solid Metal Plate Shielding Calculations

This subsection outlines methods of evaluating the performance of solid metal plate shielding in terms of attenuation (dB). It is assumed that the plate shielding has been applied to conform with the construction requirements of Section 5.3.3.2.

The attenuation afforded by solid metal plate shielding is essentially independent of the dimensions of the shielded volume, provided this volume exceeds about ten feet on a side (1000 cubic feet). Because of the increased concentration of magnetic flux in proximity to any form of shielding, attenuation will usually be less at distances within about five feet of a shield than farther away. Figure 5.24 relates shielding degradation (dB), or depreciation in attenuation, with distances in feet from a solid steel plate shield. This chart is directly applicable to buildings of heights from 15 feet to 45 feet and lengths from 45 feet to 300 feet. Shields for buildings with dimensions larger than those given by the chart will actually have less degradation or better shielding in proximity to the plates; the improvement can be considered as an increased safety factor.

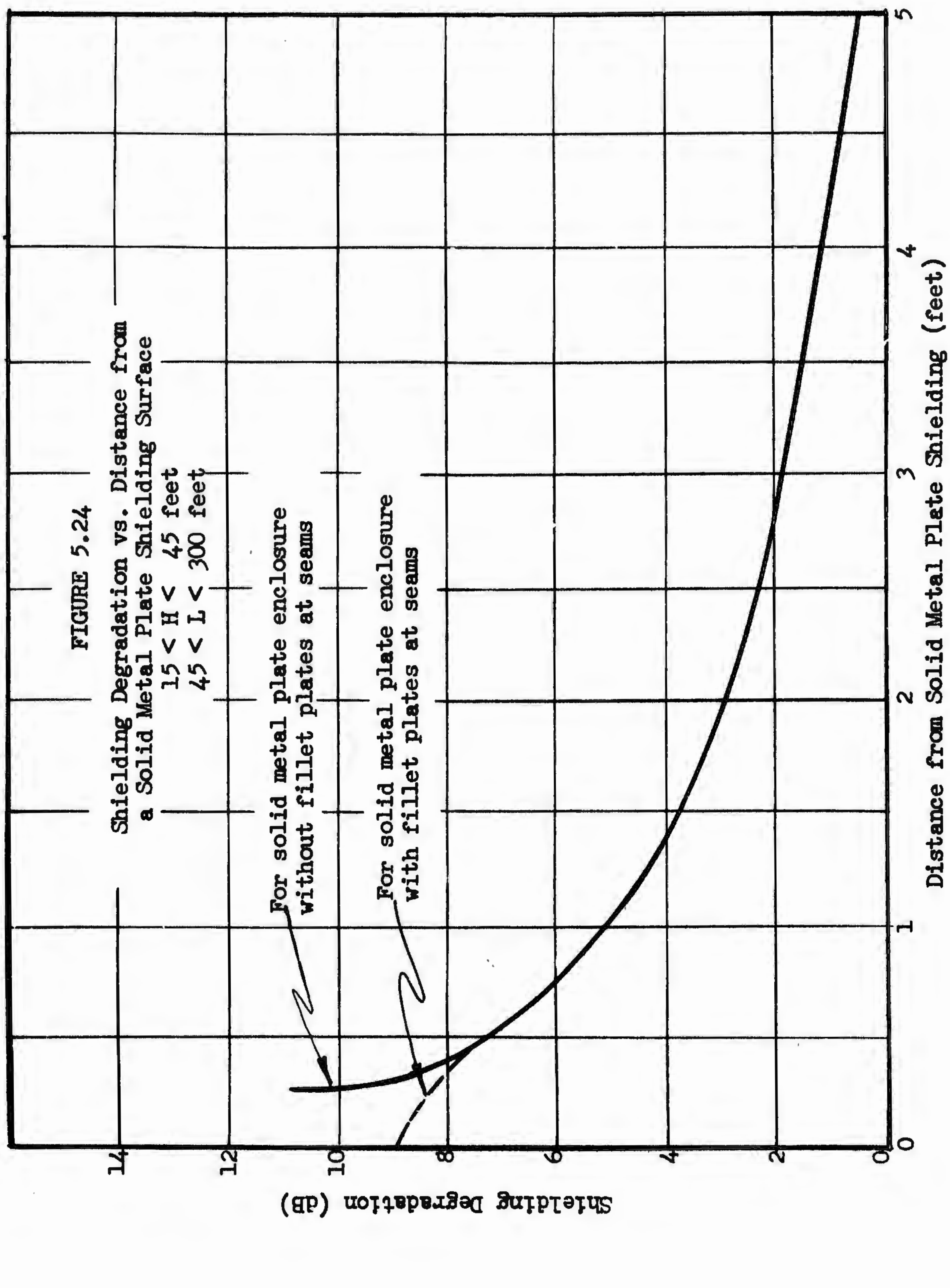


FIGURE 5.24

Shielding Degradation vs. Distance from a Solid Metal Plate Shielding Surface

$15 < H < 45$ feet

$45 < L < 300$ feet

The maximum, or "center-volume", attenuation obtainable with a completely sealed steel plate enclosure, assuming a shield conductivity (σ_o) of 6.5 x 10^6 mhos per meter and relative permeability (μ_r) of 50 is given in Figure 5.25. This chart correlates shielding attenuations in dB with plate thickness ranging from 25 mils (.025 inch) to 275 mils (.275 inch). The attenuations given do not take into account proximity to shielding surfaces, parametric variations in plate conductivity and permeability, or the effects of openings and penetrations. Each of these will be dealt with in the examples which follow:

Example 1:

Steel plate of 150 mils thickness, having the conductivity and permeability for which Figure 5.25 is applicable, completely encloses a volume. The center-volume shielding attenuation, read from Figure 5.25, is about 93 dB.

To determine net attenuation up to six feet away from steel plate shielding surfaces, use Figure 5.24 to obtain the shielding degradation in dB, then subtract this from the center-volume attenuation. Assuming that the steel plate forms the outside of a wall 24 inches thick, from Figure 5.24 a degradation of approximately 3 dB will be present two feet from the steel plate shielding. Thus, the net attenuation for equipment located against an inside wall would be 93 - 3 = 90 dB.

If the steel plate shielding is on the inside surfaces of the enclosure and fillet plates have been installed, a degradation factor of 9 dB would be read from Figure 5.24. The enclosure would then have a net shielding attenuation of 93 - 9 = 84 dB for equipment placed against the wall.

Example 2:

The attenuations in Example 1 were based on steel plate having a thickness of 150 mils, a relative permeability of 50, and an electrical conductivity of 6.5 x 10^6 mhos/meter. For a steel plate of different

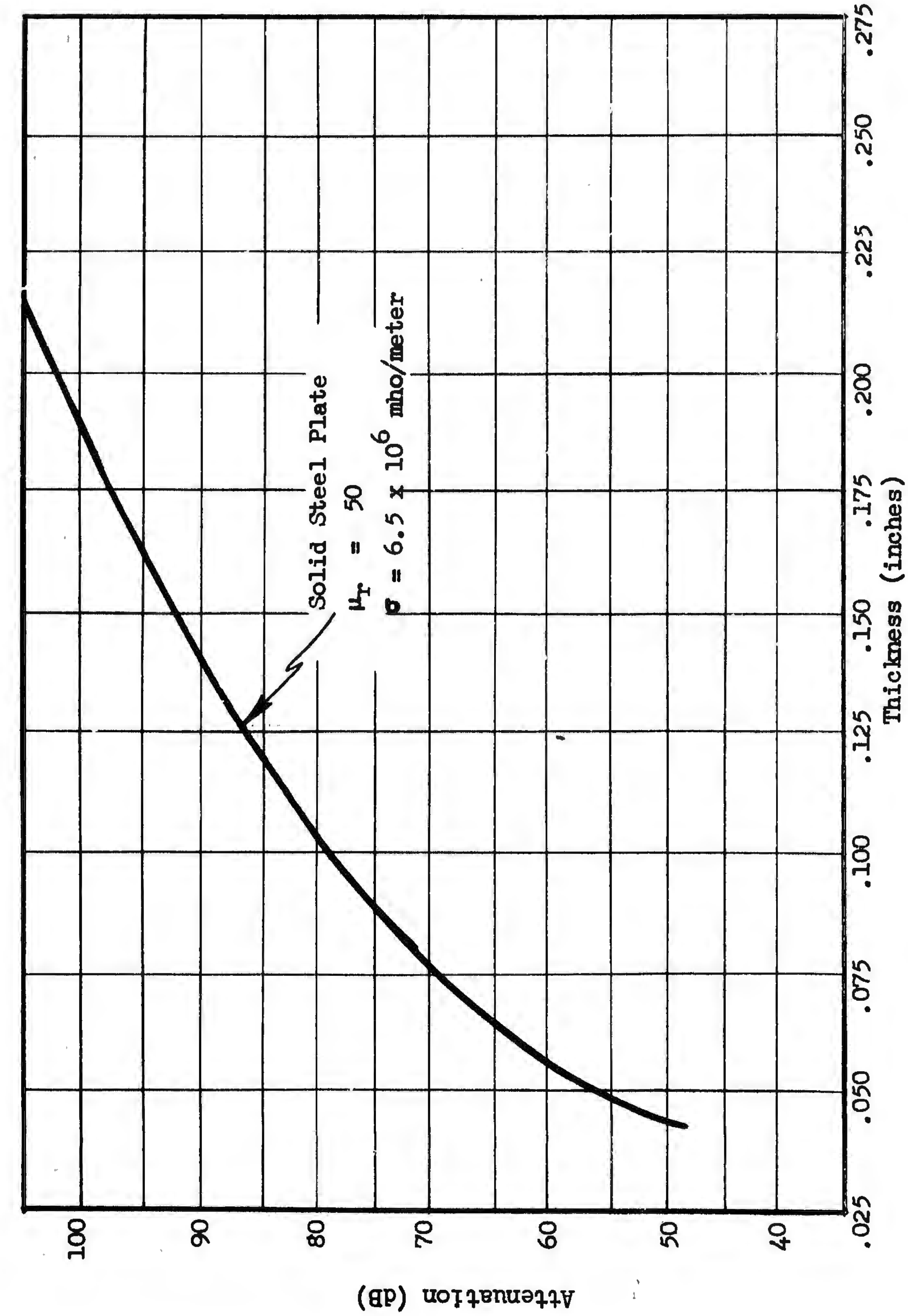


FIGURE 5.25 Center-Volume Attenuation Inside a Completely Sealed Solid Metal Plate Enclosure of Thickness Indicated

thickness, conductivity, or permeability, center-volume attenuation can be found as follows:

On the nomogram (Figure 5.26) align the value of electrical conductivity (σ_o) of the steel plate material with the plate thickness (δ) in mils and locate the corresponding point on the uncalibrated turning axis (T). Then align this point with the relative permeability (μ_r) of the steel plate material and read the center-volume shielding attenuation on the dB scale. Assuming a plate conductivity of 5×10^6 mhos/meter, a plate thickness of 50 mils and plate relative permeability of 200, the center-volume attenuation of a completely enclosed structure or room would be approximately 75 dB.

Example 3:

The nomogram, Figure 5.26, can also be used for finding the steel plate thickness that will provide a specified shielding attenuation. As an example, in Section 2.1.1 the control room shielding required under protective recommendations Plan A is at least 40 dB. It has been shown that because of proximity effects, shielding may be degraded as much as 9 dB close to an inside wall shielded with steel plate (Figure 5.24). Therefore, 50 dB of attenuation at center-volume would barely meet the protective measure requirements. Assume that the required center-volume attenuation is 75 dB to allow for a reasonable safety margin and some coordination tolerance. By use of the nomogram, 75 dB attenuation could be obtained with 60 mil steel plate for shielding, assuming a relative permeability of 100 and an electrical conductivity of 6.5×10^6 mhos/meter. Based on U. S. Standard Sheet Steel data, #16 gauge (0.0598 inch) plate weighing 40 ounces per square foot could be specified for the shielding.

It should be noted here that entirely different considerations may dictate the actual choice of the type and thickness of metal plate shielding. Such factors as structural strength, weight, weldability, relative

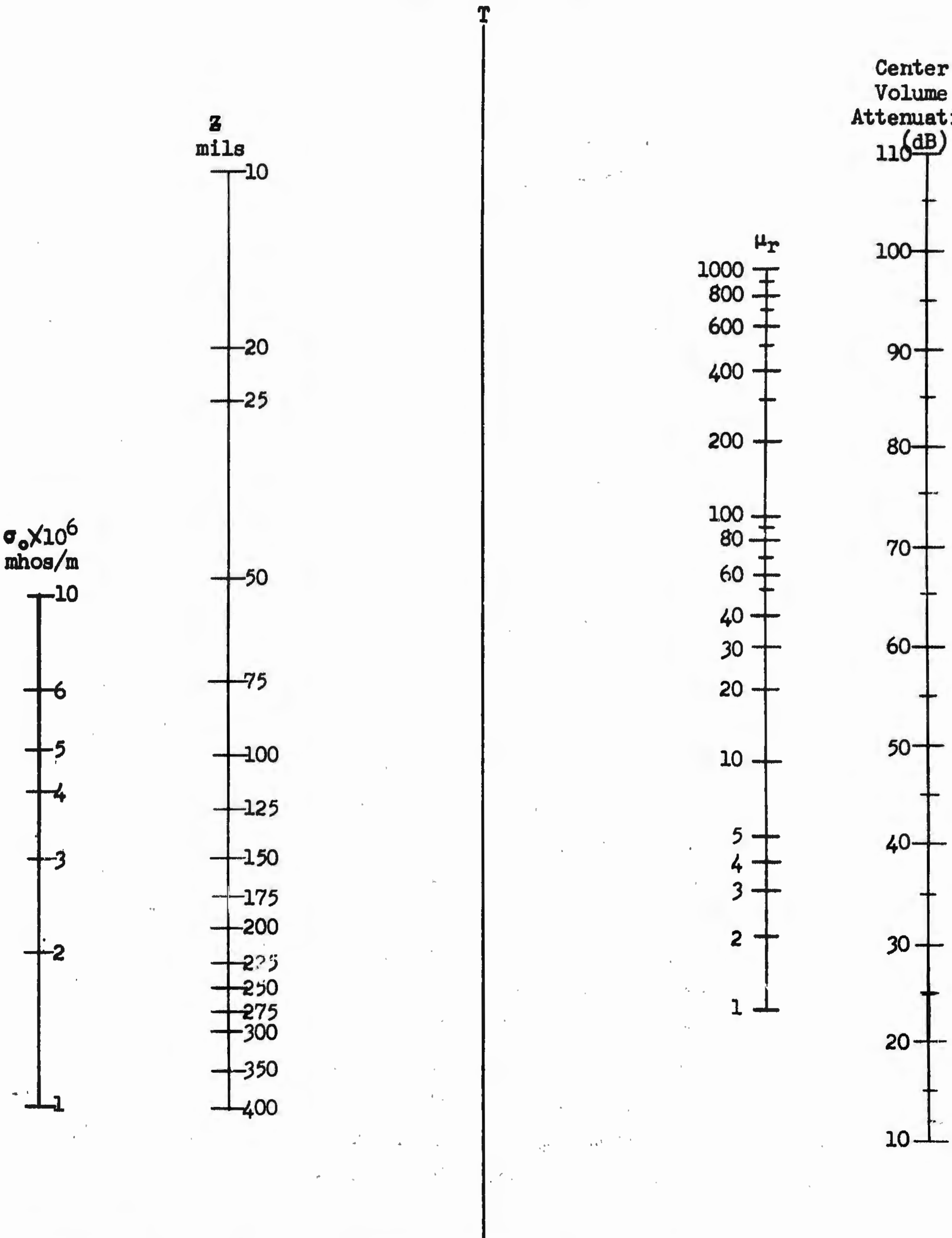
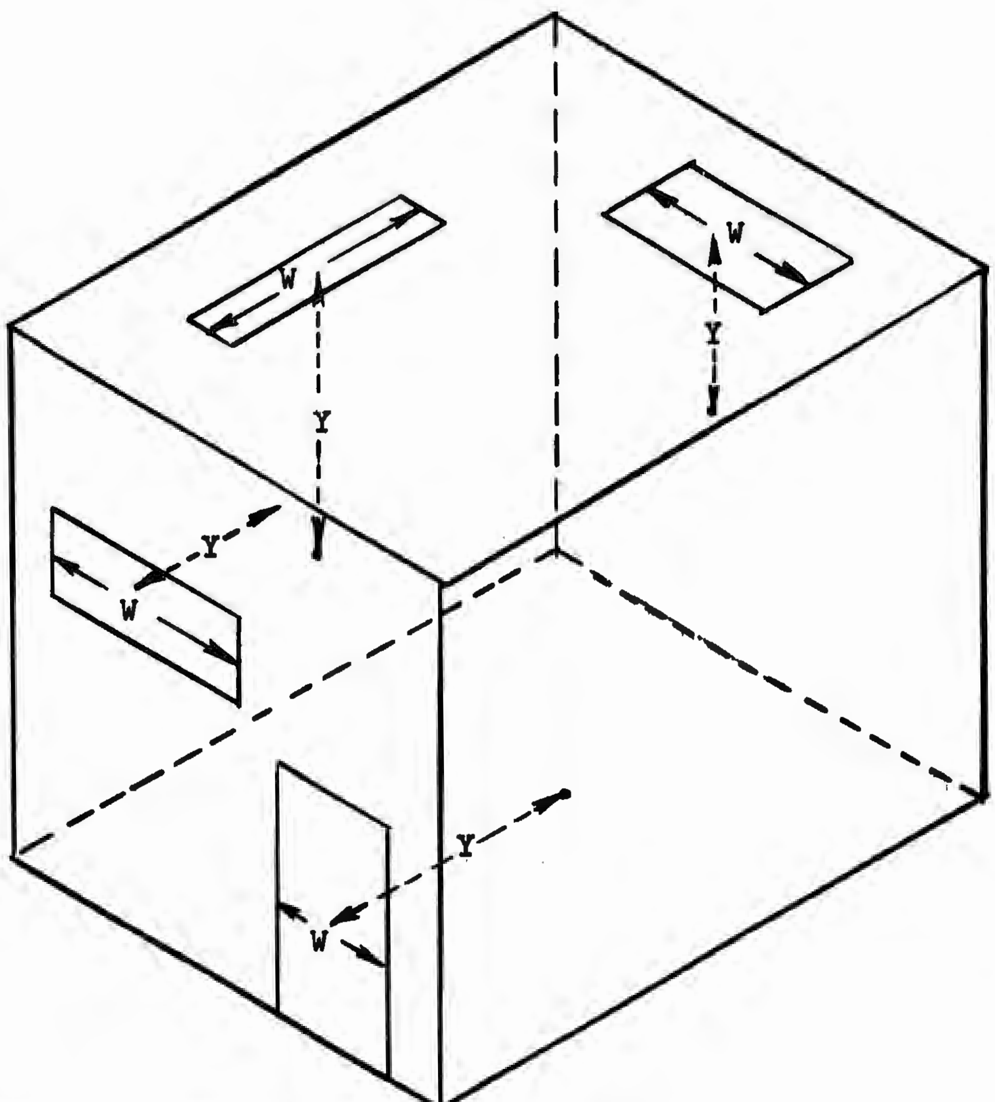


FIGURE 5.26 Shielding Nomogram Relating Steel Plate Conductivity (σ_o), Thickness (Z), and Permeability (μ_r) with Center Volume Attenuation (dB)

corrosiveness, availability, ease of handling, and cost must be considered. In any case the effectiveness of the chosen shield should be evaluated to be certain that the EMP protective recommendations in Section 2.0 are met.

Openings in metal plate shielding for doorways, ventilators, ducts, exhaust and intake plenums, etc. will significantly degrade the attenuation of shielded structures or equipment rooms in the vicinity of the opening. Figure 5.27 shows how such openings are defined in terms of an opening dimension (W) in the direction of the horizontal H-field and a distance from the opening (Y). Note that in the vertical plane the opening dimension (W) may or may not be the largest dimension but for an opening in the horizontal plane, (W) is always the largest dimension. Figure 5.28 shows how much attenuation can be expected as (Y) varies with respect to (W) for a single opening. For rooms whose center room attenuation is 50 dB or less, use the appropriate curve as given. For rooms whose dimensions do not permit a (Y) distance to be large enough so that the center-volume attenuation of the room with an opening does not reach the center-volume attenuation of the room with no openings, use an attenuation curve on Figure 5.28 corresponding to the attenuation reached for the maximum (Y) permitted by the room dimensions. For instance, assume a 10' x 10' x 10' room having a 50 dB center-volume attenuation with no openings. Assume a 7' x 3' door opening is desired. To determine whether the 50 dB curve would apply for this case, calculate the maximum Y/W ratio that the room size permits. A Y/W of 10/3 = 3.33 related to the 50 dB curve results in an attenuation of 42 dB. This, then, becomes the new center-volume attenuation for the room and identifies the curve to be used to determine attenuations with respect to the 7' x 3' opening.

To maintain the shielding effectiveness of a structure or equipment room at the recommended requirements, metal wave guides (sleeves) as shown in Figure 5.29 can be installed in openings. Wave guides cannot be used where it is necessary to bring conduits, metal piping, or other metal



W = Largest opening dimension in the horizontal field direction.
Y = Distance from the opening.

FIGURE 5.27 Openings in Shielding

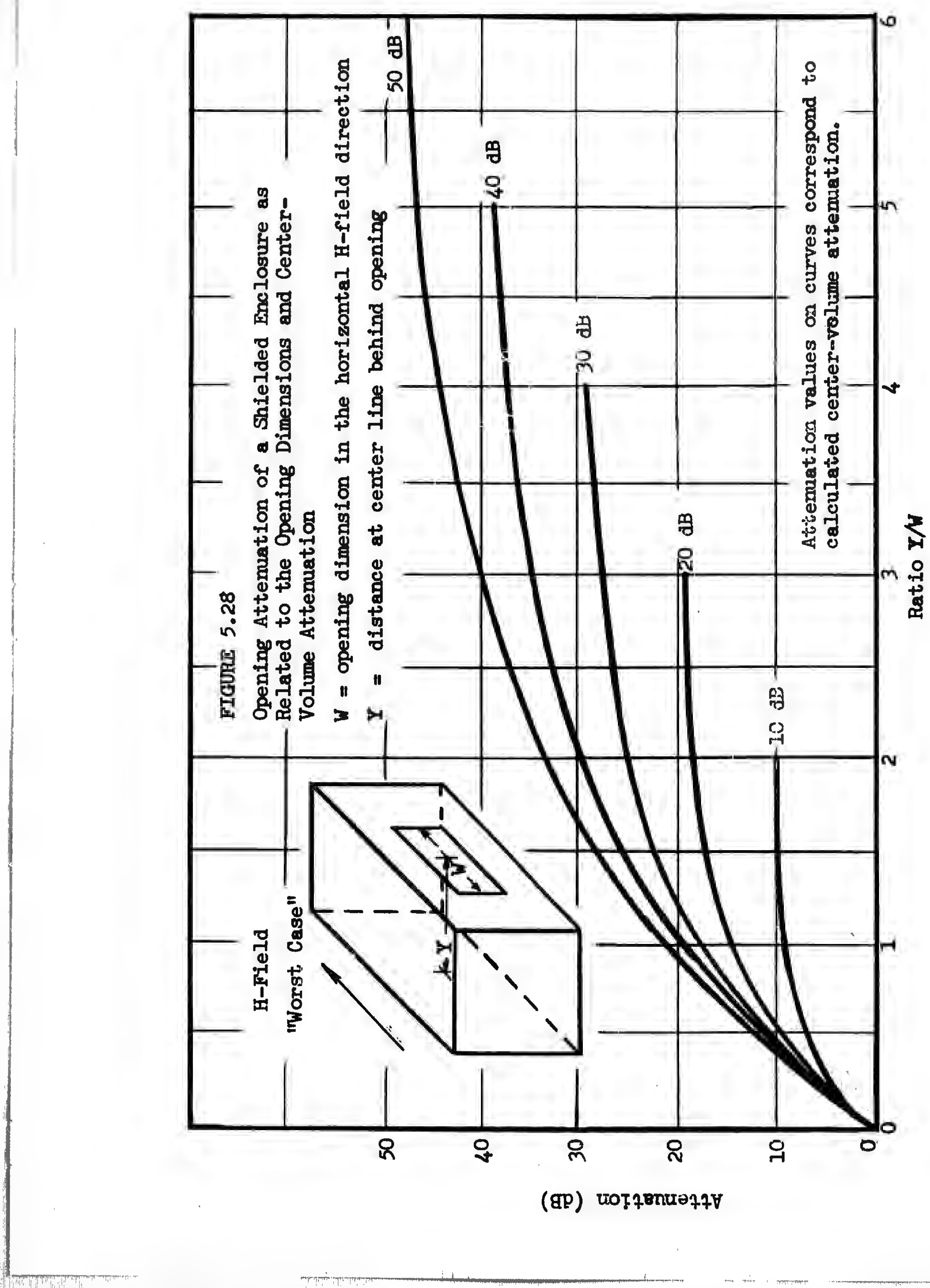


FIGURE 5.28

Opening Attenuation of a Shielded Enclosure as Related to the Opening Dimensions and Center-Volume Attenuation

W = opening dimension in the horizontal H-field direction

Y = distance at center line behind opening

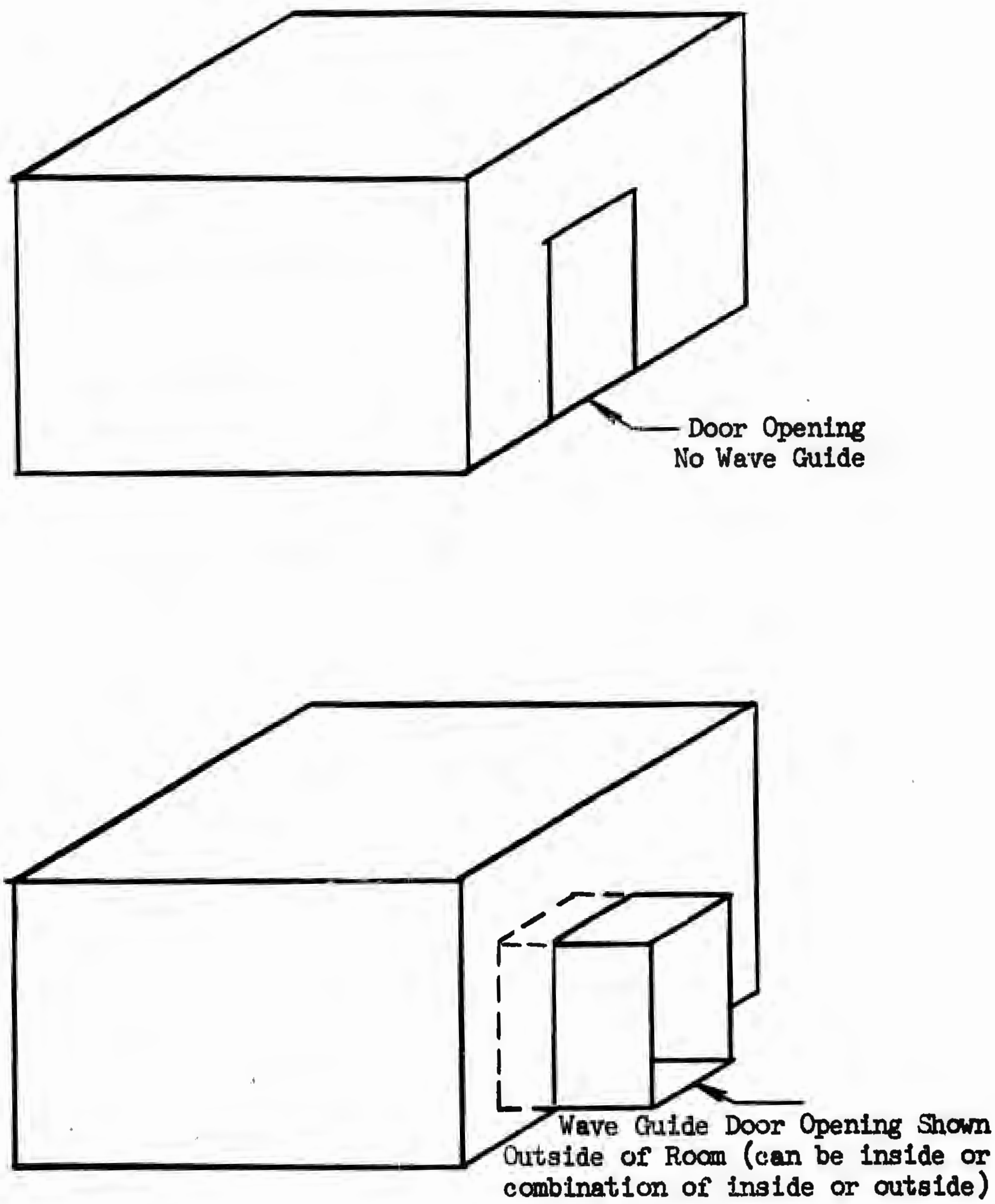


FIGURE 5.29 Application of Wave Guides

conductors through an opening into a metal plate shielded area (Section 5.3.2.2). The following example shows how wave guide proportions are found.

<u>Example 4</u>:

To determine the wave guide length and width dimensions for a required shielding attenuation level, enter the graph on Figure 5.30 at the required attenuation level and read the Y/W ratio. Assume that an attenuation level of 50 dB must be maintained in a room or building. The Y/W ratio corresponding to 50 dB is 2.5. Therefore, the length (Y) of the wave guide must be 2.5 times the largest width dimension (W). Actual placement of the wave guide can be inside or outside the room or a combination of both as shown in Figure 5.29.

5.3.4 EMP Shielding for Structures and Large Equipment Rooms by Reinforcing Steel Bars (Rebars)

5.3.4.1 Areas of Application - Introduction to EMP Shielding by Rebars

Section 5.3.4 covers the application of reinforcing steel bars (rebars) as shielding for structures and large equipment rooms.

The steel rods (rebars) used in reinforced concrete building construction can afford EMP shielding for such hardened buildings and the rooms within them, provided the rebars are welded to form continuous loops around the volume to be shielded (Figure 5.31).

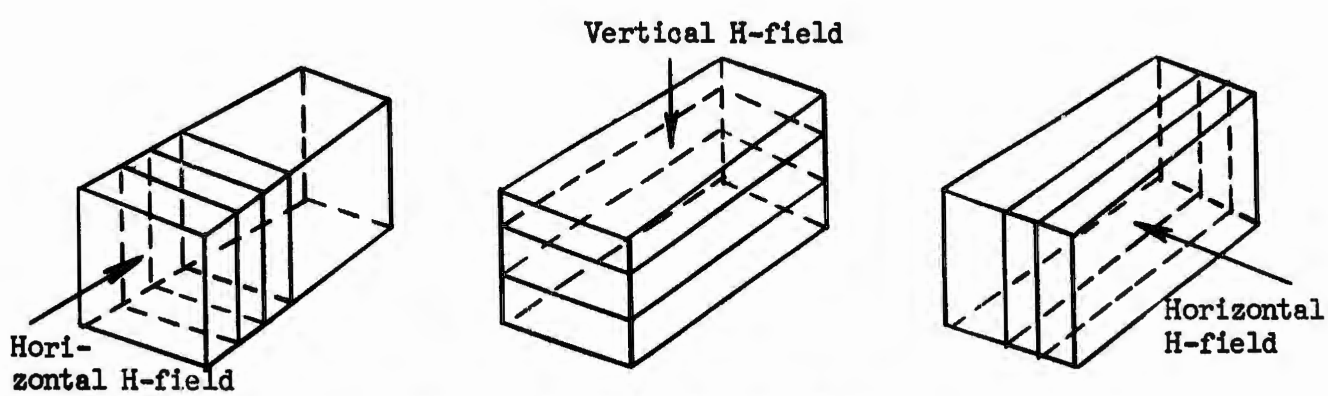


FIGURE 5.31 Reinforcing Steel Rod Loops

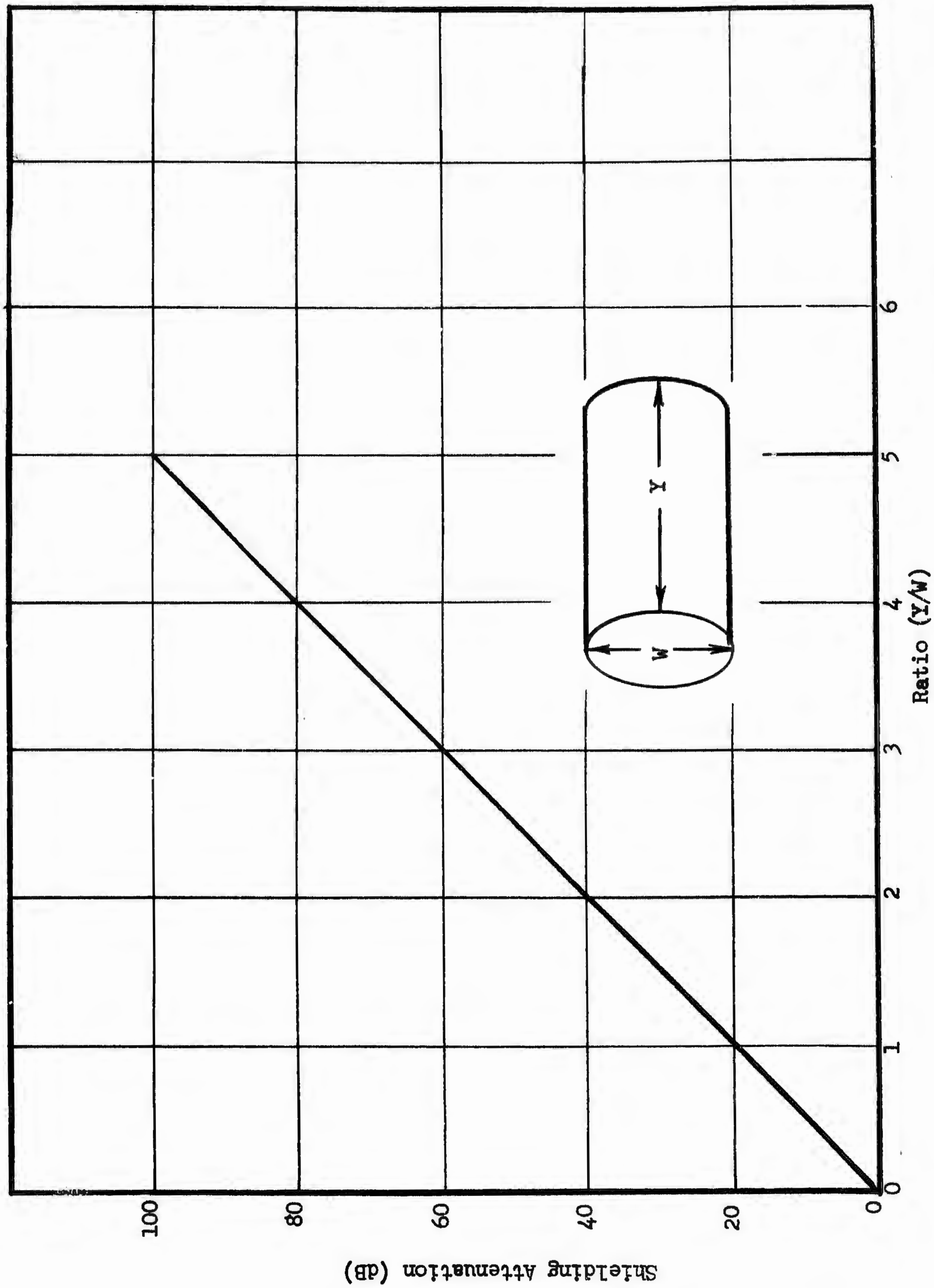
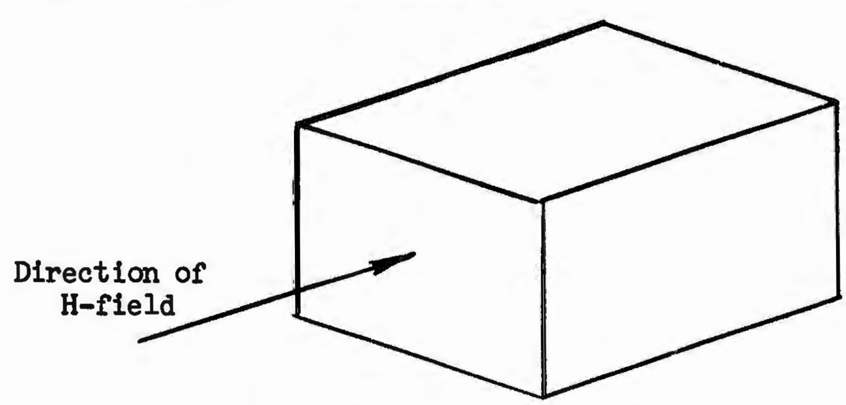


FIGURE 5.30 Wave Guide Attenuation as a Function of Wave Guide Dimensions

The continuous rebar loops must be positioned at right angles to the H-field in order to achieve the greatest shielding effect. To shield against an H-field from any direction, the loops must be continuous in all three dimensions, as shown. Thus, the shielding effects of steel reinforcing bars is produced by circulating currents through the bars in all four walls as well as those in the floor and ceiling of the structure. This points out the need for providing good electrical connections by welding all bars and joints between bars at corners and edges along walls, ceiling and floor.

Graphical information and calculations to be presented later (see Section 5.3.4.3) give the shielding attenuations provided by rebars for rooms and buildings of various sizes using various combinations of rebar diameter and spacings.

Assuming a uniform spacing of rebars in all outside surfaces of a shielding volume, analyses indicate that minimum attenuation, or poorest shielding representing a "worst case" condition, occurs within the given volume when the direction of the magnetic field is parallel to the longest dimension of the volume, as shown below.



In Figure 5.32 is shown a rebar shielding scheme for a horizontally directed H-field. Note that only the uppermost and lowermost horizontal perimeter rebars need be welded to form rebar loops in a horizontal plane. The vertical rebars are welded to these horizontal rebar perimeter loops as shown.

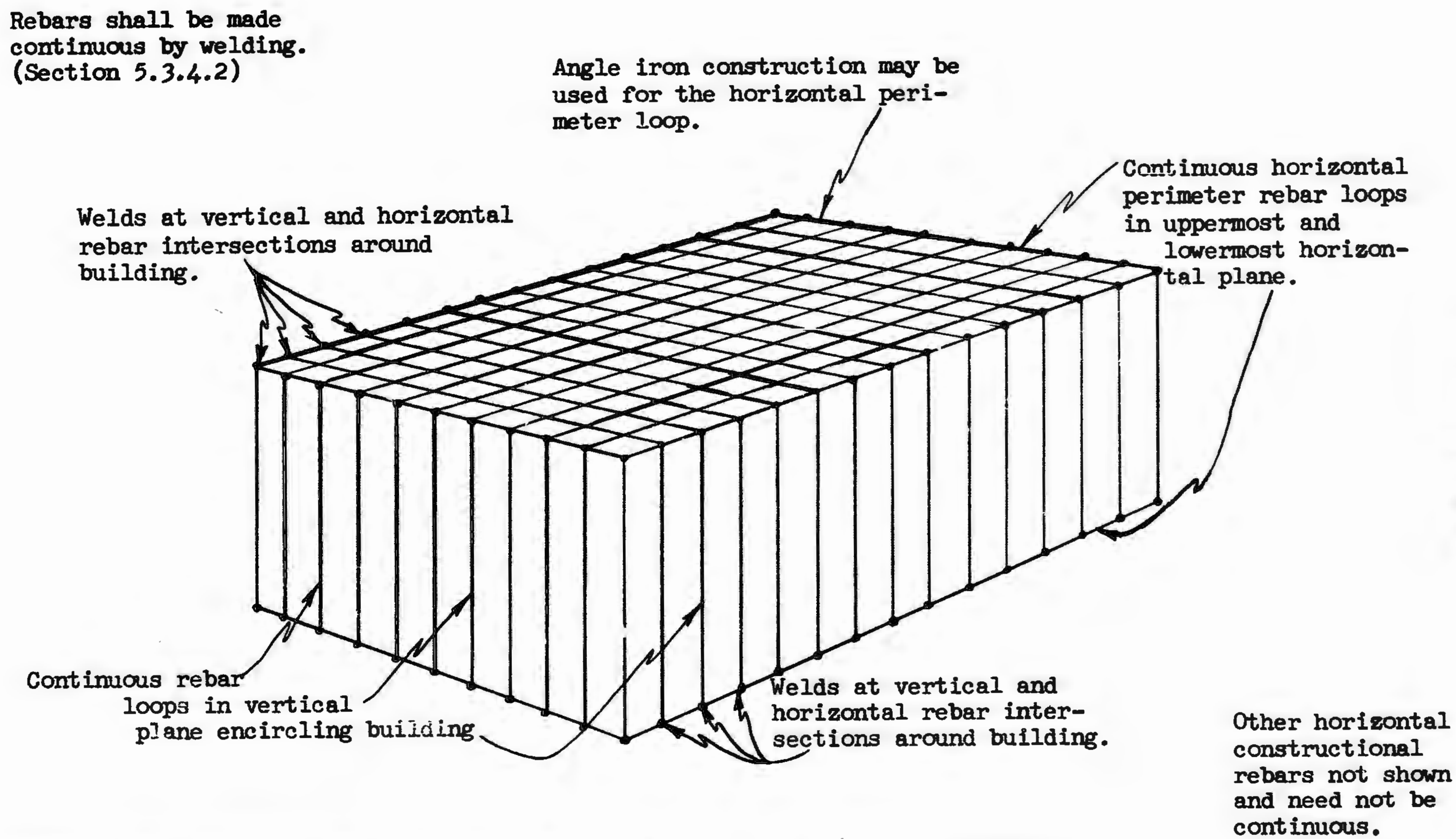


FIGURE 5.32 Overall Building Rebar Shielding Scheme for Horizontal H-Field

Additional attenuation for improved shielding can be obtained if double rebar loops are used in the building construction. This requires welding the inner rebars and the outer rebars in loops as shown in Figure 5.33. The cages formed by the inner and outer rebars do not have to be electrically distinct. The inner and outer rebars may connect wherever required for structural reasons.

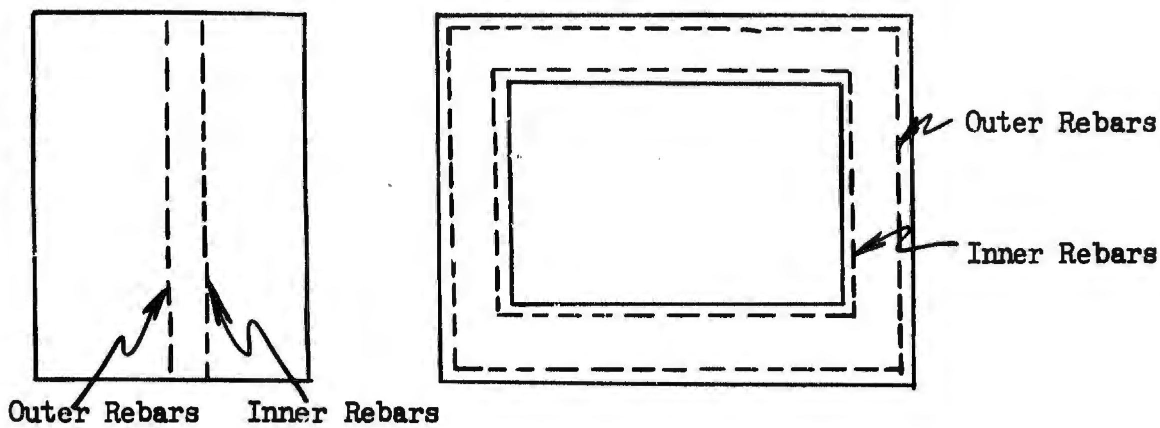


FIGURE 5.33 Double Reinforcing Bar Loops

Studies indicate that EMP field attenuation by means of rebar shielding is influenced by a number of variable parameters, including field orientation, building or room dimensions, rebar diameter and spacing, rebar conductivity and permeability, single or double cage construction, and the integrity of workmanship, as well as the effects of openings and penetrations. Techniques of evaluating rebar shielding, taking these factors into account, are presented in Section 5.3.4.3.

5.3.4.2 Construction Practices for Rebar Shielding

For building construction steel reinforcing rods (rebars) to function properly as EMP shields, required construction practices are as follows:

1. Rebars shall be welded together to form continuous loops in all

three dimensions enclosing the building. Welds shall be made to conform with construction details shown in Figure 5.34.

2. If loops of rebars enclose two or more rooms, the internal wall (partition) rebars do not have to be welded. (Figure 5.35).
3. When openings are required in a rebar-shielded structure for doorways, ducts, plenums, etc., all rebars around the opening shall be made electrically continuous by being welded to a metal plate or rebar encasing the opening. (Figure 5.36)
4. Metal utility piping and electrical conduits entering a rebar shielded structure from outside shall be connected to the building grounding system at the point of entrance, as shown in Figures 5.10, 5.11, and 5.15.

5.3.4.3 Attenuation Calculations for Reinforcing Steel Rod (Rebar) Shielding

This section covers techniques of evaluating the EMP shielding afforded by rebars, including the effects of penetrations and openings.

In evaluating the shielding attenuation (dB) afforded by rebars, it will be assumed that the construction practices prescribed in Section 5.3.4.2 have been followed and that the structure to be shielded has "worst case" orientation with respect to the incident EMP field. The attenuation provided by rebar shielding will then depend upon the following factors:

1. The size and shape of the volume to be shielded.
2. The rebar diameter and spacing.
3. The electrical conductivity (σ_o) of the rebars.
4. The relative permeability (μ_r) of the rebar material.
5. Proximity of ceilings, walls, or floors containing rebars.
6. The size of shielding discontinuities created by openings and penetrations.

Effects of each of these factors upon rebar shielding will now be considered in detail and working examples will be given.

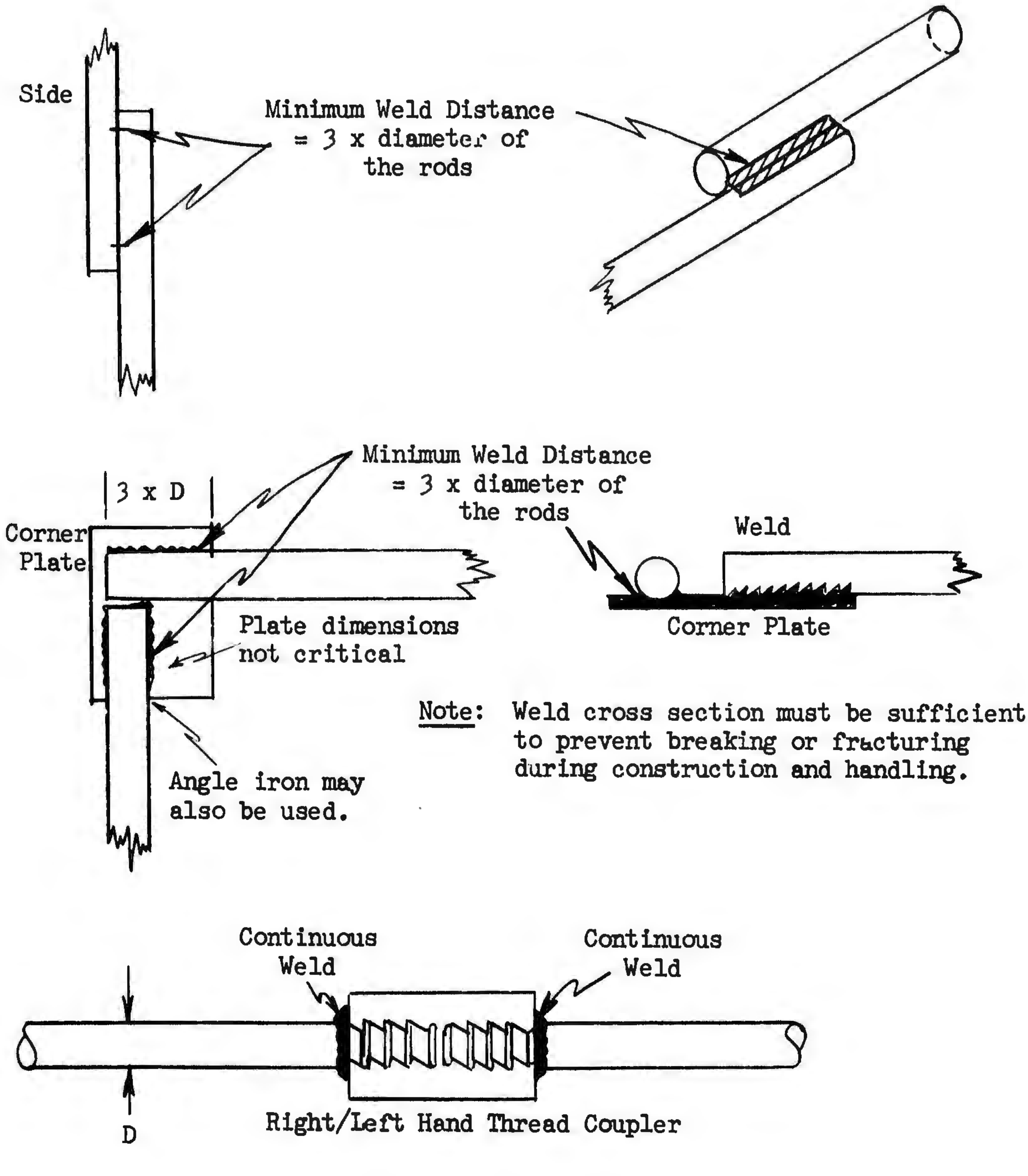


FIGURE 5.34 Reinforcing Steel Rod (Rebar) Welding Details

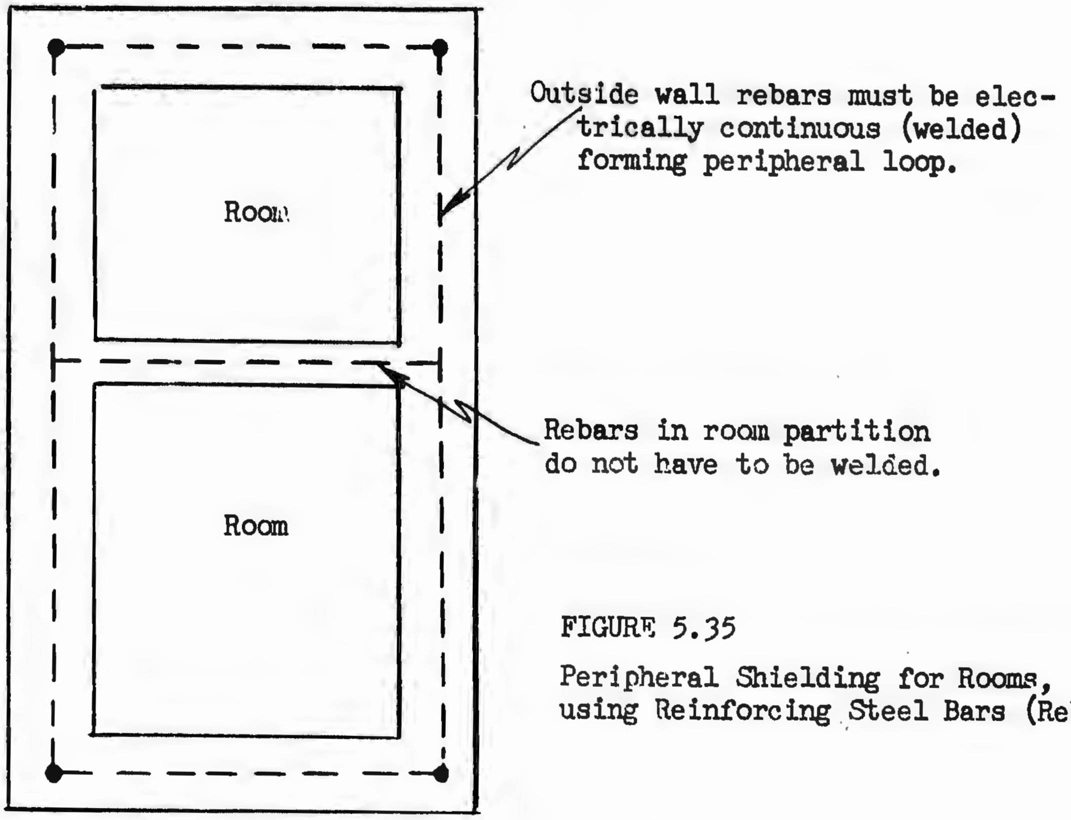


FIGURE 5.35

Peripheral Shielding for Rooms, using Reinforcing Steel Bars (Rebars)

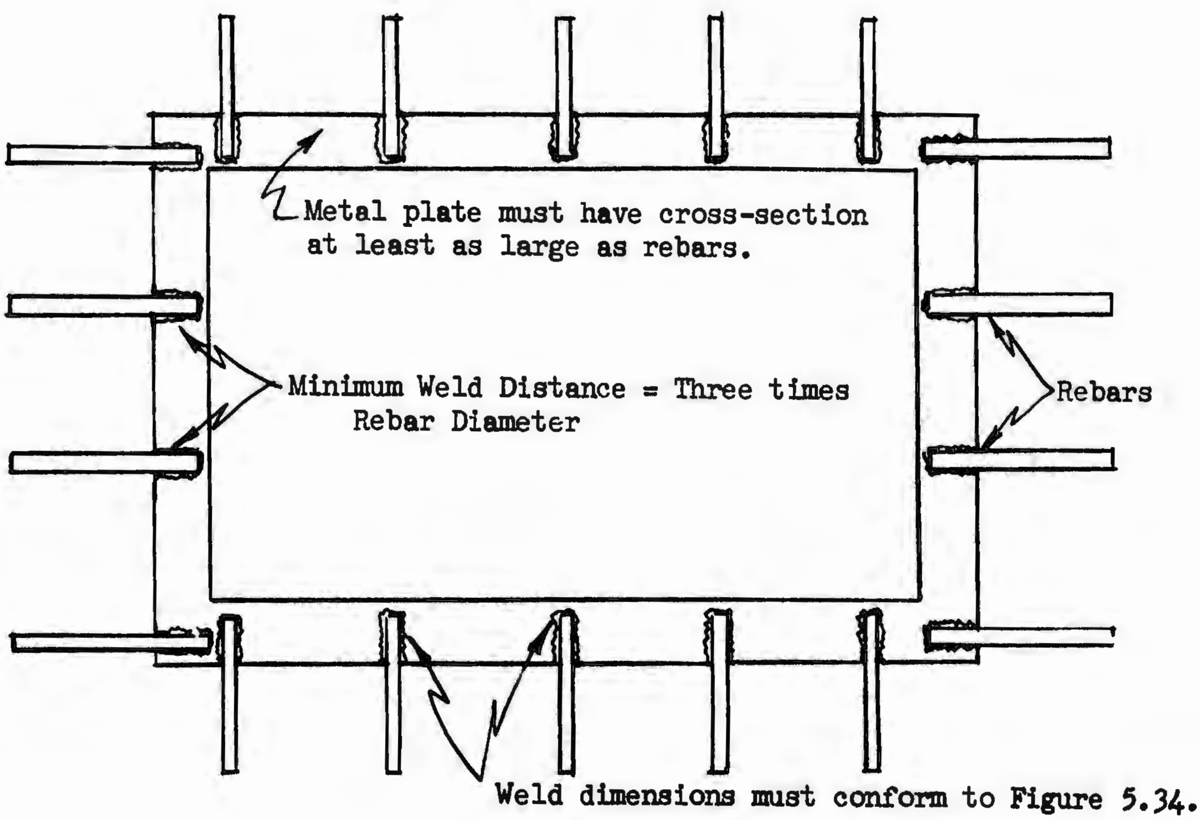


FIGURE 5.36 Termination of Rebars at an Opening

Rebar shielding effectiveness is influenced by structure dimensions and proportions. Subsection 5.3.4.3.1 provides graphical data and examples for determining the "center-volume" (maximum) attenuation within a building or room having dimensions and proportions within specified practical limits. To simplify the computations, this subsection assumes standardized rebar sizes and spacings and a definite rebar conductivity and permeability. Subsection 5.3.4.3.2 gives general equations and a number of graphs that can be used to determine the attenuation for wide variations in structure size and shape, rebar diameter and spacing, and rebar conductivity and permeability.

For situations where the rebar diameters and/or the spacing between rebars are not constant within a wall, ceiling, or floor, using the existing minimum rebar diameter and maximum spacing combination for calculation purposes will yield conservative results. In subsections 5.3.4.3.1 and 5.3.4.3.2, curves for evaluating the effects of variations in bar diameter and spacing are presented.

5.3.4.3.1 Rebar Shielding Calculations, Assuming Fixed Values of Conductivity and Permeability

Calculations involving shielding by rebars are considerably simplified if their electrical conductivity, permeability, diameter, and spacing are assumed to be within the practical limits associated with normal construction practices.

In the following calculations of rebar attenuation, a conductivity value of $\sigma_o = 6.5 \times 10^6$ mho/meter and a permeability value of $\mu_r = 50$ have been used. These calculations are valid for conductivities ranging from 4.0×10^6 mho/meter to 8.0×10^6 mho/meter and for relative permeabilities ranging from 10 to 100. An investigation of chemical analysis of all grades of ASTM A15, A408, A431, and A432 steel reinforcing bars indicates that the conductivity and relative permeability for these rebars will be in the above ranges.

The diameter of the rebars and the distance between rods will depend on

structural considerations of the building design. Attenuations afforded by rebars ranging from nominal size #6 (0.75 inch diameter) to nominal size #18-S (2.257 inches diameter) have been calculated with spacing varying from less than seven inches to more than 22 inches. The attenuation data presented are valid and conservative for actual rebar spacings within two inches of design spacings, provided that the average space between bars $\left(\frac{\text{length of wall}}{\text{number of bars-1}}\right)$ is within 10 per cent of design spacing. Bar diameter may also vary 10 per cent from the nominal values.

The variations in building or room size (shielding volume) are presented in the series of curves on Figures 5.37 and 5.38 covering ranges applicable to the power plant building. The height of the shielding volume has been assumed to be 15 feet in Figure 5.37 and 30 feet in Figure 5.38. Its other dimensions (width and length) may vary over a 5 to 1 range.

For various room proportions use the following criteria for curve selection:

1. Height 15 feet to 24 feet - use curves for 15 feet (Figure 5.37)
2. Height 24 feet to over 30 feet - use curves for 30 feet (Figure 5.38)
3. For variations of the width (J) dimension - use curve equal to or less than the value.
4. For dimensions smaller or larger than the graphs provide, use subsection 5.3.4.3.2 as the basis for shielding calculations.

The curves of Figures 5.37 and 5.38 are valid only for a single course of 1.692 inch diameter rebars spaced 14 inches on centers. Additional curves shown in Figure 5.39 provide correction factors ($\pm \Delta$ dB) to calculate the changes in attenuation for other rebar spacings and other rebar diameters.

The curves of Figure 5.39 are also applicable for double-course rebar construction, if the double-course construction is assumed to be equivalent to a single-course construction with half the double-course rebar spacing.

Table 5.2 lists several attenuation correction factors read from Figure 5.39 applying to common rebar configurations.

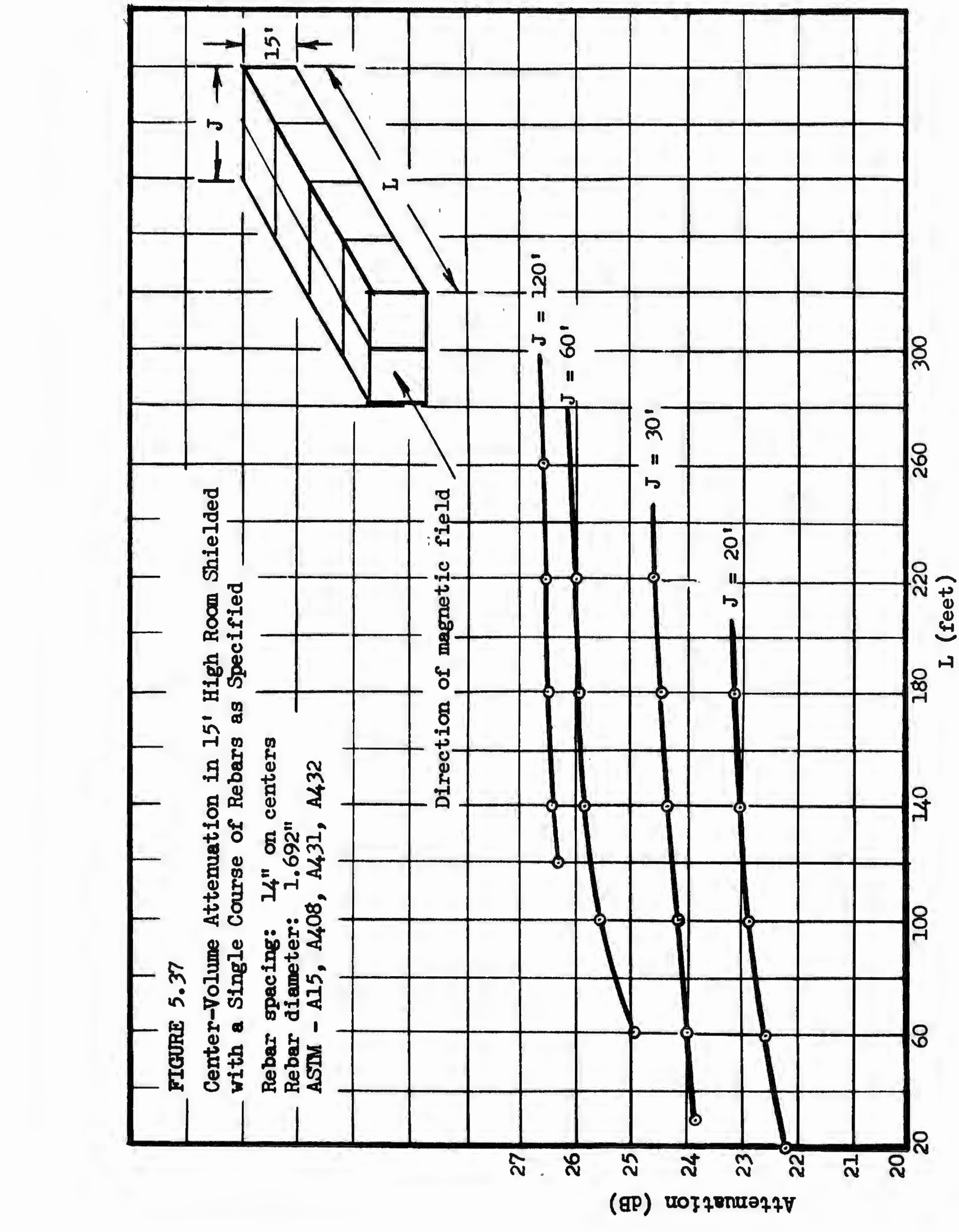


FIGURE 5.37

Center-Volume Attenuation in 15' High Room Shielded with a Single Course of Rebars as Specified

Rebar spacing: 14" on centers
Rebar diameter: 1.692"
ASTM - A15, A408, A431, A432

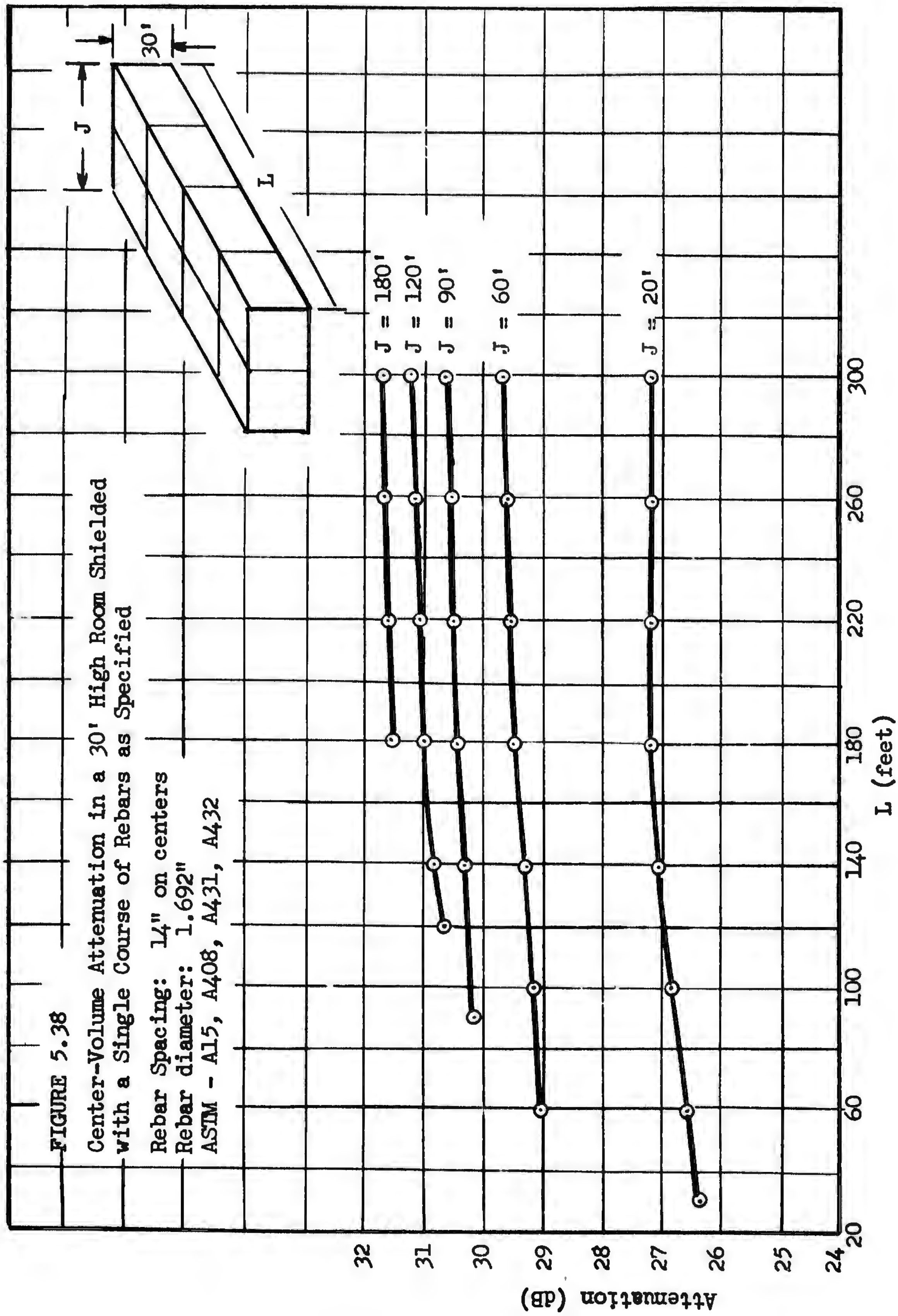


FIGURE 5.38

Center-Volume Attenuation in a 30' High Room Shielded with a Single Course of Rebars as Specified

Rebar Spacing: 14" on centers
Rebar diameter: 1.692"
ASTM - A15, A408, A431, A432

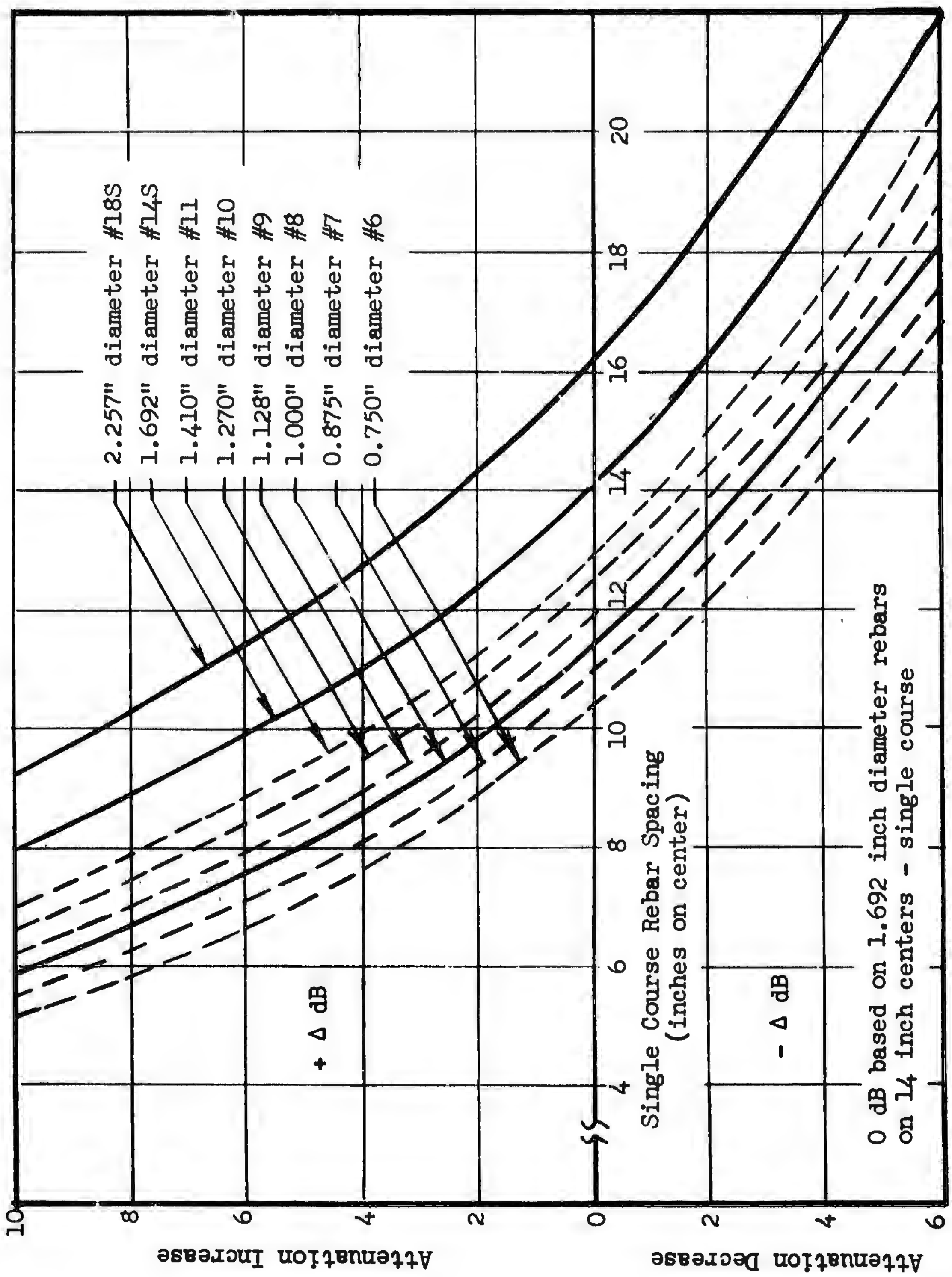


FIGURE 5.39 dB Correction Curves for Various Rebar Configurations

TABLE 5.2

APPLICABLE ATTENUATION CORRECTION FACTORS
FOR SEVERAL SELECTED REBAR CONFIGURATIONS

Type of Configuration and Parameters			Attenuation Increment
Rebar Diameter inches	Rebar Spacing inches	Construction	Δ dB
2.257	12	Single course	+ 5
1.692	14	Single course	0*
1.000	18	Single course	- 6
2.257	20**	Double course	+ 8.5
1.692	14	Double course	+ 13
1.000	16	Double course	+ 5

* No dB corrections are necessary for a single course of 1.692 inch diameter rebars on 14 inch centers because these were the basis for Figures 5.37, 5.38, and 5.39.

** For double course of rebars 20 inches on centers, use single course equivalent 10 inches on center in Figure 5.39.

The attenuation value is found on Figures 5.37 and 5.38 and corrected, if necessary, applying the increments (± Δ dB) shown in Figure 5.39 and Table 5.2. This value applies only to the center portion of the shielded volume. Attenuation is not constant throughout a shielded volume; there will usually be less attenuation (more degradation of shielding) with increasing proximity to the rebars. Figure 5.40 shows the increase in degradation with respect to distance from ceilings, walls, or floors shielded by rebars; this is applicable to buildings of heights ranging from 15 feet to 45 feet and lengths ranging from 45 feet to 300 feet. Degradation values given in Figure 5.40 must be subtracted from the center-volume shielding effectiveness values found from Figures 5.37, 5.38, and 5.39 in order to determine attenuations within five feet of a ceiling, wall, or floor.

When outside rebars of a wall are used for shielding, there will be appreciable wall thickness between these rebars and equipment placed against

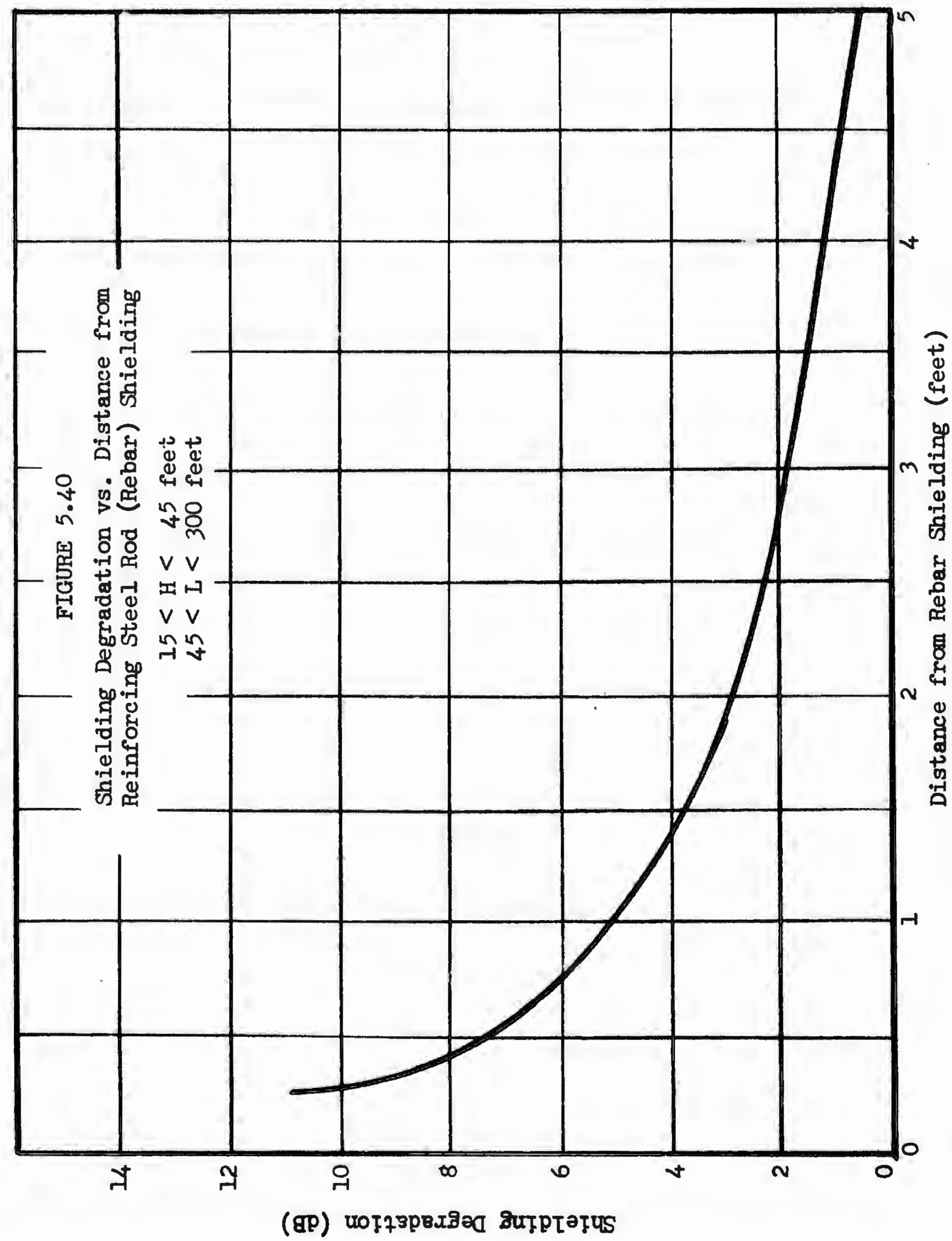


FIGURE 5.40

Shielding Degradation vs. Distance from Reinforcing Steel Rod (Rebar) Shielding

$15 < H < 45$ feet
$45 < L < 300$ feet

an inside wall. When making shielding calculations, this distance must be considered and added to the physical spacing between the wall and the equipment. For constructions using both inner and outer courses of rebars for shielding, the innercourse of rebars will be comparatively close to equipment placed against an inside wall. In this case there will be additional attenuation provided by the double course rebar construction; however, this increased attenuation will be largely offset by reduced attenuation caused by equipment proximity to the inner course rebars. (Equipment placed six feet or more from the wall would, of course, benefit fully from the double rebar shielding.)

The following set of sample calculations will exemplify the methods of obtaining the center-volume attenuation and the net attenuation at a shielding surface for both single and double course rebar constructions.

Given Rebar Height (H) = 18 feet
Rebar Width (J) = 32 feet
Rebar Length (L) = 145 feet

Rebars are single course, diameter 1.41 inches ± 10 percent on 15-inch centers. Conductivity (σ_o) and permeability (μ_r) are within the limits given (σ_o from 4×10^6 mhos/meter to 8×10^6 mhos/meter and μ_r from 10 to 100).

Perform the following computations:

Total number of rebar loops perpendicular to H-dimension $= \frac{18}{15/12} =$ 14 minimum

Total number of rebar loops perpendicular to J-dimension $= \frac{32}{15/12} =$ 25 minimum

Total number of rebar loops perpendicular to L-dimension $= \frac{145}{15/12} =$ 116 minimum

Example 1: Single Course Rebar Construction

Since H = 18 feet, use Figure 5.37 for H = 15 feet. Using curve for J = 30 feet and L = 145 feet, read attenuation for 24.3 dB. From Figure 5.39, apply correction factor for single course 1.41 inch diameter rebars of - 2 dB. Attenuation at the center of the shielding volume is then

24.3 - 2 = 22.3 dB. This will be the attenuation in the building beyond six feet of any shielding rebars.

Assume that the rebars used for shielding are the outside rebars and that the wall thickness between the inside wall of the room and the rebars is a minimum of 22 inches (1.83 feet). Equipment placed against this wall would be subject to a shielding degradation of approximately 3 dB, as indicated by Figure 5.40. Equipment at the wall would then be shielded with a net attenuation from the rebars of 22.3 - 3 = 19.3 dB.

Example 2: Double Course Rebar Construction

If double course rebar shielding construction on 15-inch centers is used and assuming the spacing between rebar courses is between d/2 and 2d where d is distance between rebars in one course, the attenuation in the center of the room would be:

24.3 dB	from Figure 5.37
+ 8.8 dB	from Figure 5.39
33.1 dB	with double course rebar construction

For equipment against the wall assume that the inner rebars are three inches or 0.25 feet from an inside wall of the room. From Figure 5.40 the degradation would be 10 dB, or - 10 dB attenuation.

Net attenuation from the double course of rebars for equipment against the wall is then:

33.1 dB	in center volume with double course rebar construction
- 10.0 dB	from Figure 5.40
23.1 dB	net

Discontinuities in rebar shielding, caused by openings and penetrations, will adversely affect the attenuation of the shielded volume in the vicinity of the opening. Attenuation effects, due to openings in shielding shown in Figure 5.27, are defined in terms of two dimensions; the dimension (not the diagonal) of the opening (W) in the direction of the horizontal H-field and distance within the shielded area from the opening (Y). Figure 5.28 shows how much the attenuation is affected as (Y) varies with respect to (W).

This graph can be used to determine the values of attenuation at varying distances from a known size opening or to find the maximum permissible width of an opening if equipment is to be placed at some known distance from the opening, assuming some allowed attenuation; or it can be used to find the clearance that must exist from a given width opening to maintain some specified value of attenuation.

An example of attenuation calculations for an opening follows.

Example 3:

Assume that a building with single course rebar shielding has a center-volume attenuation of 20 dB and an attenuation of 18 dB next to a shielded wall. A doorway into the room is 8 feet high and 3 feet wide.

The opening dimension (W) in the direction of the horizontal H-field is then the doorway width of 3 feet. Refer to Figure 5.28 and, from the curve that becomes asymptotic to the center volume attenuation (20 dB), read ratio Y/W of approximately three. This means that a distance Y = 3 x W = 3 x 3 = 9 feet inside the room from the doorway opening, the attenuation will be the same as in the center of the room. For equipment facing the doorway and less than 9 feet away from it, the attenuation will be less. Figure 5.28 indicates that with equipment at least 4 feet away from the doorway opening, with ratio Y/W = 4/3 = 1.33, the attenuation there would be about 17 dB.

If the shielding effectiveness of a particular room with openings must be maintained at the center-volume attenuation level, wave guides (metal sleeves) as shown in Figure 5.29 can be installed in openings. This figure depicts a shielded volume with and without a wave guide at the doorway opening. To determine the wave guide length and width dimensions for a required shielding attenuation level, use the procedure as given in Example 4.

Example 4:

Assume an 8' x 3' doorway opening is desired for a shielded area having a center volume attenuation of 20 dB. Enter the wave guide graph (Figure 5.30) at 20 dB and find a Y/W ratio of 1.0. For wave guide, calculation (W)

is always the largest dimension of the opening. Therefore, the wave guide length Y = W x 1 = 8' x 1 = 8 feet. Actual placement of the wave guide can be inside or outside the room or a combination of both as shown in Figure 5.29.

5.3.4.3.2 Attenuation Calculation for Reinforcing Steel Rods (Rebars) Considering Variations in Rebar Conductivity, Permeability, Diameter, and Spacing - for any size structure

The shielding calculation methods outlined in this section can be applied to any size structure and also in those cases where variations in rebar conductivity, permeability, diameter, and/or spacing preclude use of the graphical methods described in Section 5.3.4.3.1.

These formal attenuation calculation methods will require certain basic information as to room or building size and knowledge of rebar parameters, as follows:

H = rebar height in room or building in meters

J = rebar width in room or building in meters

L = rebar length in room or building in meters

μ = permeability of rebars = $\mu_o \times \mu_r = 4\pi \times 10^{-7} \times \mu_r$

σ_o = conductivity of rebars in mho/meter

d_o = diameter of rebars in meters

d = spacing on centers of parallel single course rebars in meters

Briefly, the computation procedure requires the determination from graphs of several factors (K, -A, and B) based on structural proportions. These factors and the basic information above are used to determine two other constants (X and Y). These constants are used with graphs to find two other factors (U and W), which are then combined with certain given parameters into an attenuation formula. The following steps outline this procedure:

Step 1. Determination of Constant Y

$$Y = \frac{K(A + B)}{2}, \text{ where}$$

K is found on Figure 5.41 for corresponding values of H/L and H/J (limited to height-to-width proportions between 1:1 and 1:10).

-A is found on Figure 5.42 for the corresponding value of ratio d/d_o.

B is found on Figure 5.43 for the corresponding value of ratio L/d.

Step 2. Determination of Constant X

$$X = \frac{10^7 \sqrt{\mu}}{56.6\ d_o \sqrt{\sigma_o}}$$

Step 3. Determination of Factors U and W

Using the values of constants Y and X as calculated in the preceding steps, obtain corresponding values for factors U and W from Figures 5.44 and 5.45, then change the value of U read from Figure 5.41 from dB to a ratio U_R by formula:

$$U_R = \text{antilog } U/20$$

Step 4. Calculate "Center-Volume" Attenuation

$$\text{Center-Volume Attenuation(dB)} = \left[20 \log \left\{ \frac{13{,}300}{7.89 \times 10^{-6} \times U_R \times W \times \frac{d(H+J)}{2\ KHJ}} \right\} -4 \right]$$

The equation above can be used for calculating the shielding by single course rebars and also double course rebars when the spacing between courses (d_s) varies between d/2 and 2d, where d is the spacing between rebars in a single course.

→| d |←

O O O O O O O

d_s d_s varies between d/2 and 2d.

O O O O O O O

For this case, the H, J, and L dimensions can be taken from either the outer or inner rebar course. When d_s exceeds 2d, then the calculations must be made using H, J, and L dimensions associated with the innermost shielding rebars.

There may be occasion to make attenuation calculations on buildings which are "T" or "L" shaped rather than a parallelepiped. As an example, consider the "T" shaped structure below. Disect the overall area into two parallelepipeds as shown. Make separate attenuation calculations for each rectangular section. For buildings having a pyramid shape, attenuation calculations can

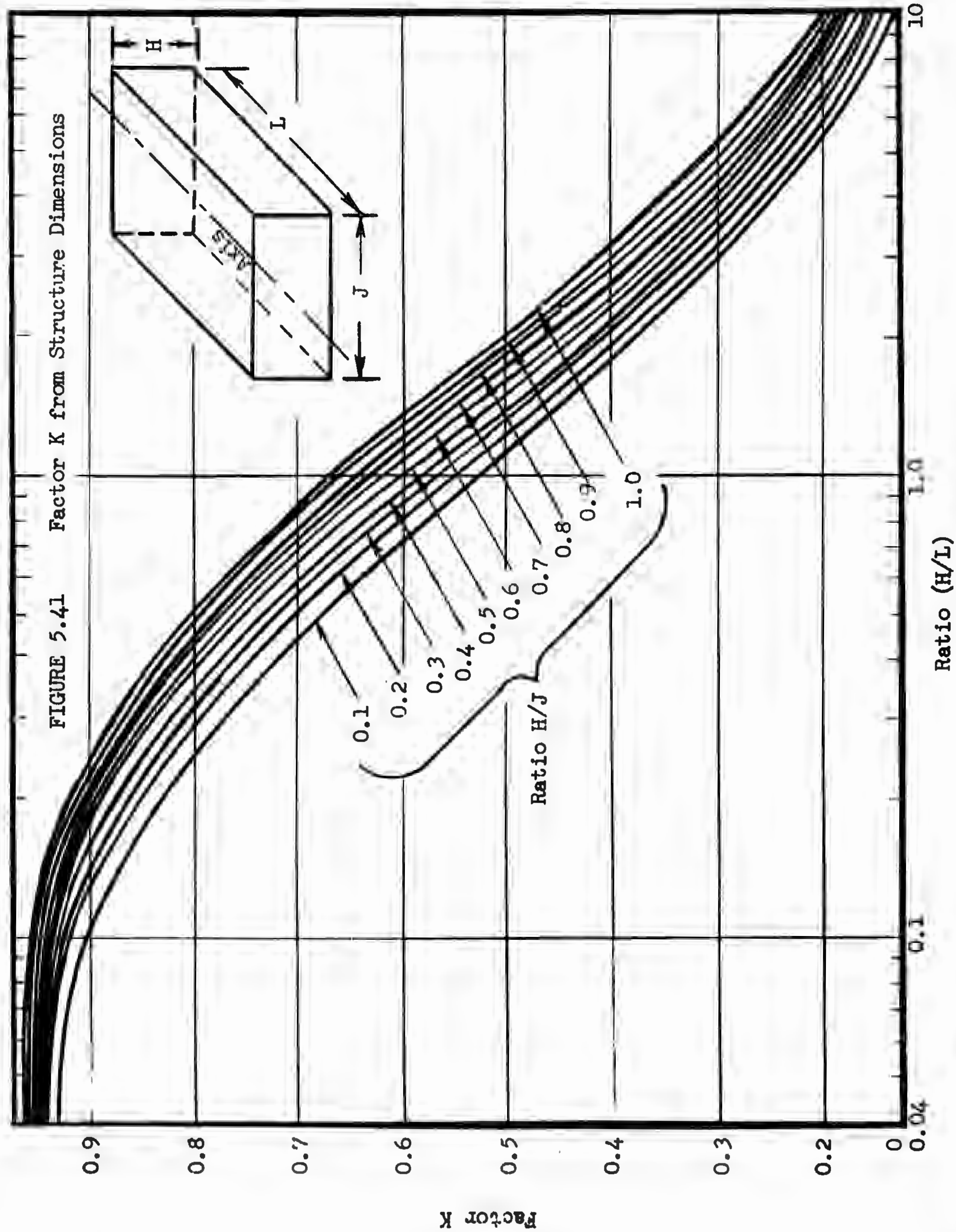


FIGURE 5.41 Factor K from Structure Dimensions

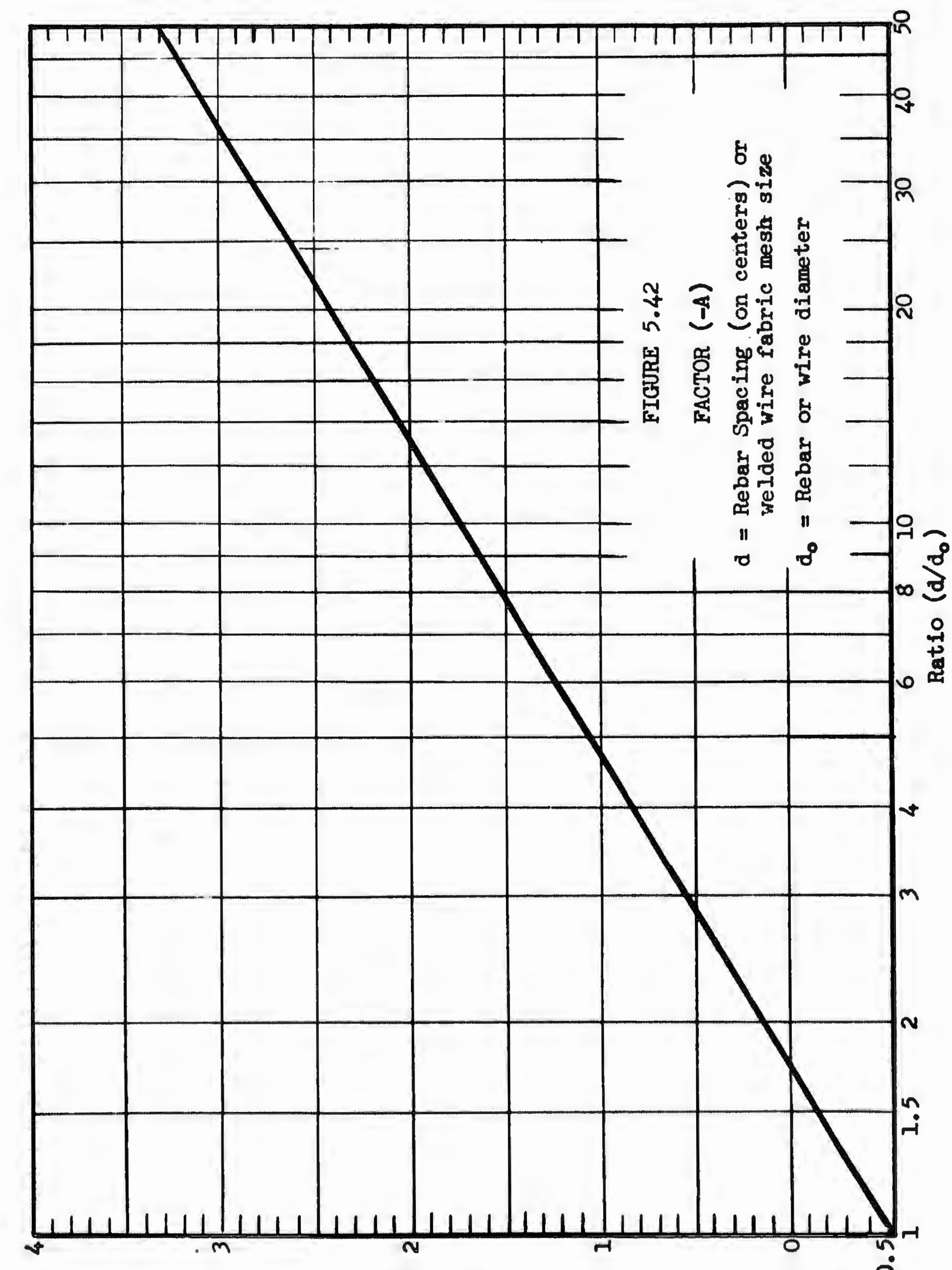


FIGURE 5.42

FACTOR (-A)

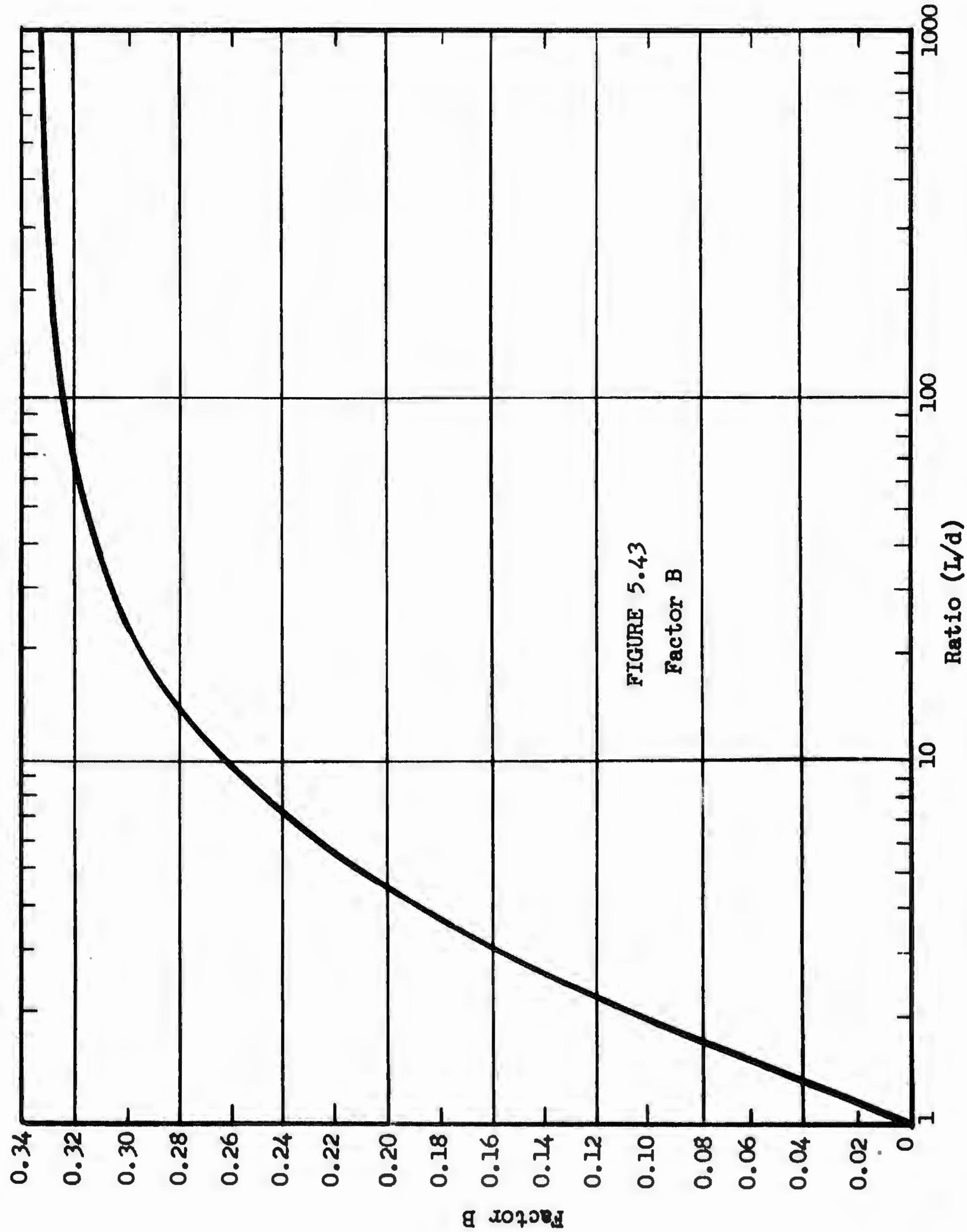


FIGURE 5.43
Factor B

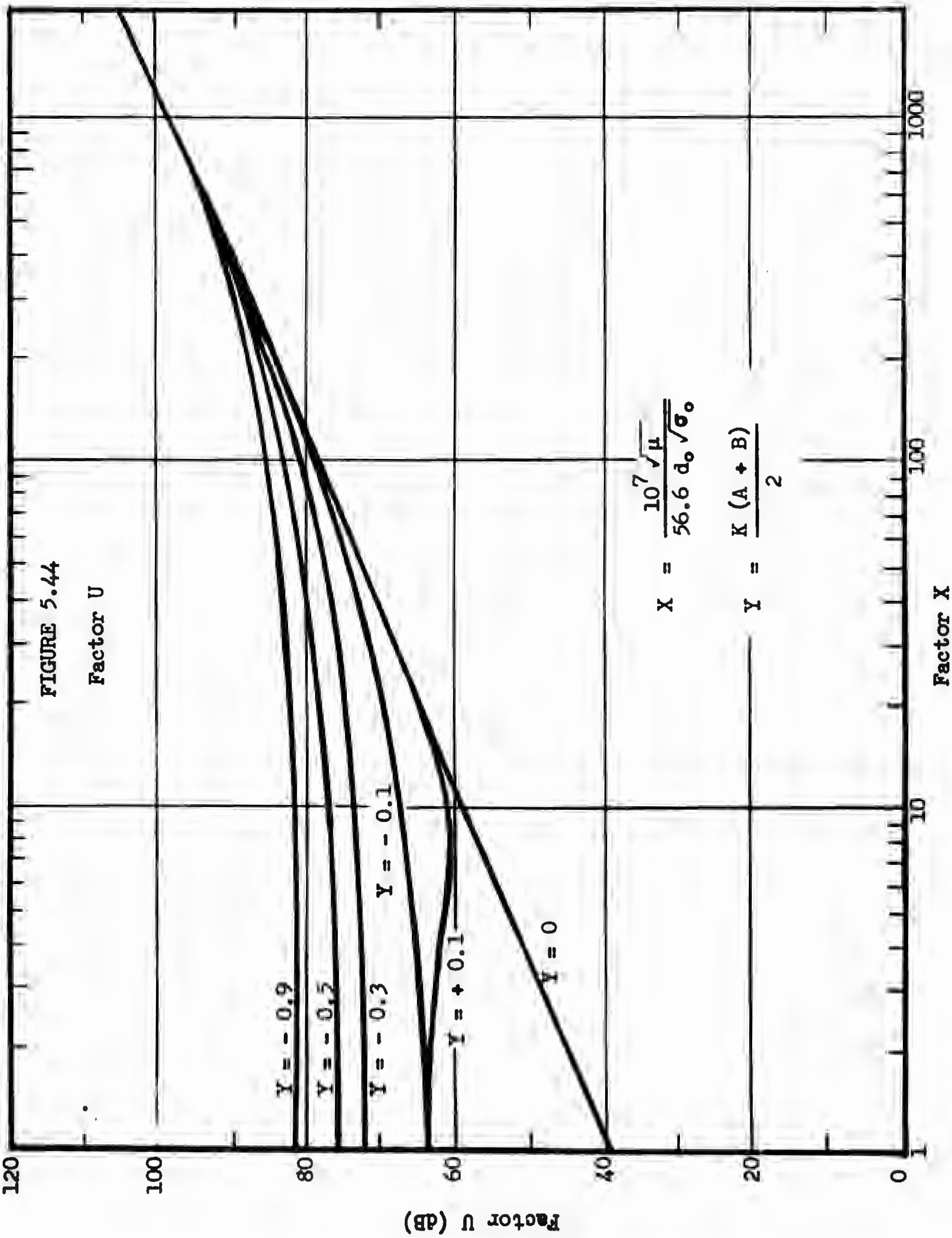


FIGURE 5.44

Factor U

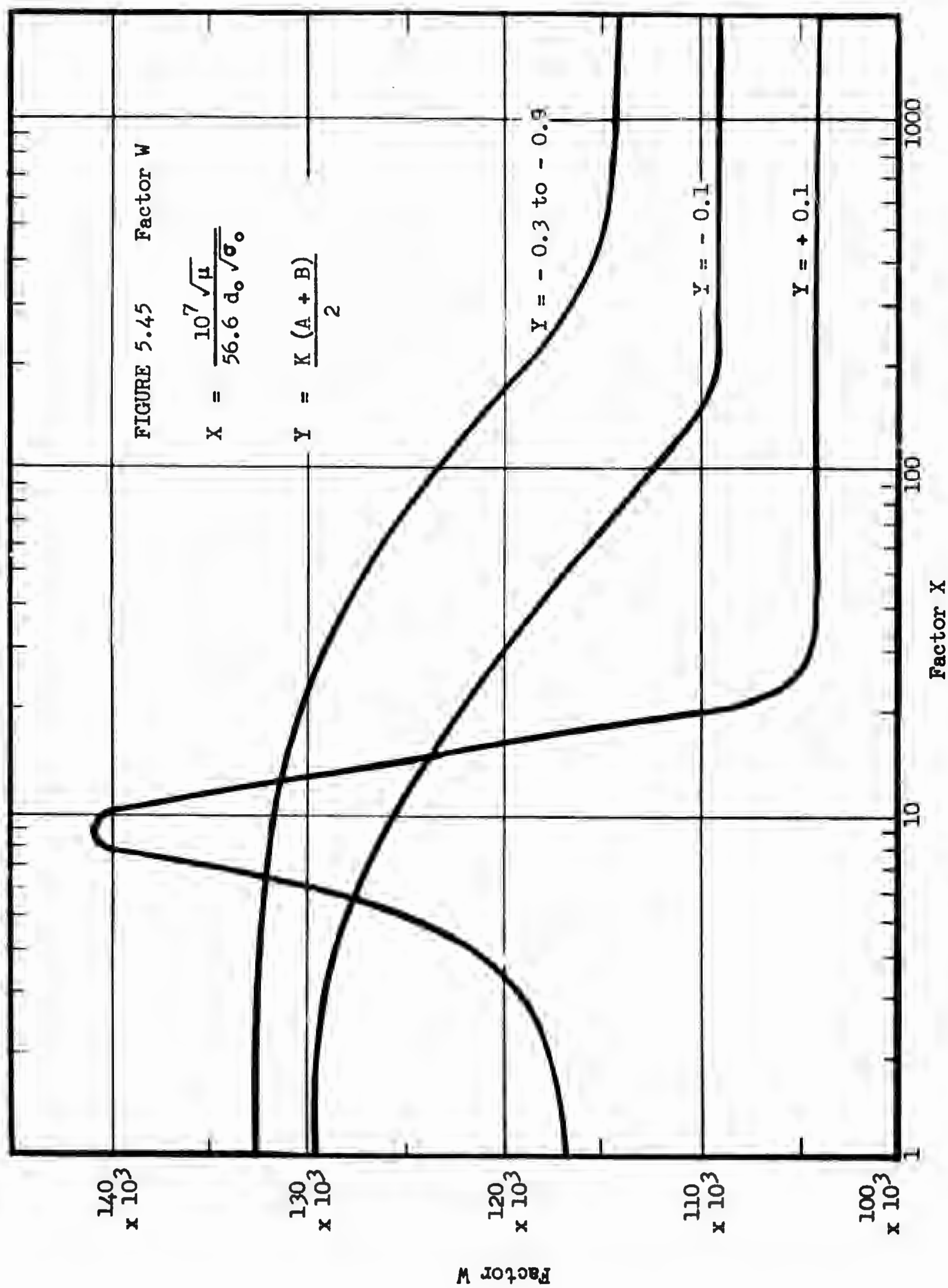
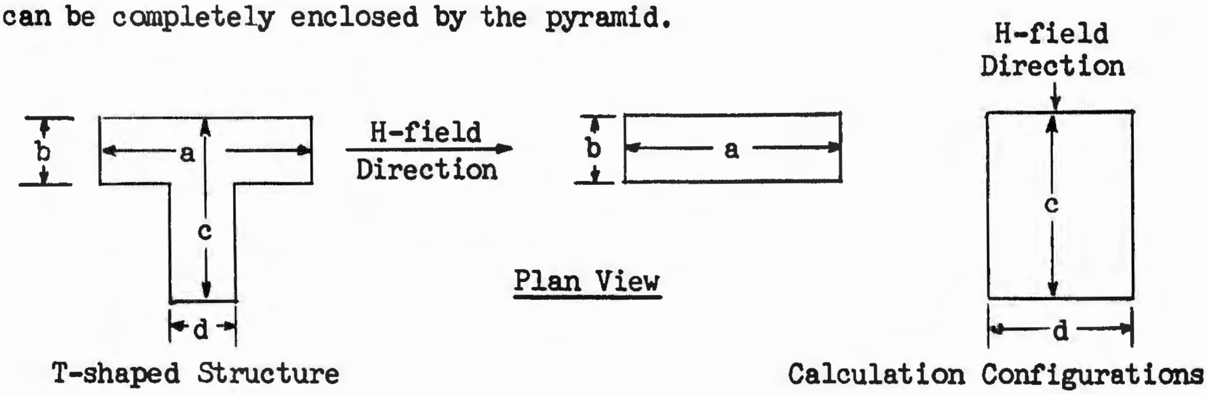


FIGURE 5.45 Factor W
X = $\frac{10^7 \sqrt{\mu}}{56.6\, d_o \sqrt{\sigma_o}}$
Y = $\frac{K\,(A + B)}{2}$
Y = - 0.3 to - 0.9
Y = - 0.1
Y = + 0.1
140 x 10^3
130 x 10^3
120 x 10^3
110 x 10^3
100 x 10^3
Factor W
1
10
100
1000
Factor X

be made by considering the building to be the largest parallelepiped which can be completely enclosed by the pyramid.



5.3.5 EMP Shielding by Application of Welded Wire Fabric

5.3.5.1 Introduction

Section 5.3.5 covers the use of welded wire fabric for shielding structures and equipment rooms.

Welded wire fabric embedded in the walls, ceiling, and floor of a room or building can provide H-field attenuation if the individual wires of the fabric are properly connected to form electrically conductive loops surrounding the volume to be shielded.

As in the case of shielding by rebars, induced currents circulating through loops at right angles to the incident H-field set up a counteracting field, so that the net field within the shielded volume is attenuated.

While the weldments at junctions of the wires forming the fabric do form small loops or meshes, these loops do not encircle or enclose the volume to be shielded. Therefore, at all edges and corners where welded wire fabric surfaces meet, it is desirable that each wire be welded or brazed to the corresponding wire in the other planes or brazed to metal strips. Suggested methods of forming these loops are detailed in Section 5.3.5.2.

Assuming that welded wire fabric of uniform mesh is applied to all outside surfaces of a shielding volume, analyses show that minimum attenuation, or poorest shielding, representing a "worst case" condition, exists

within the shielded volume when the direction of the H-field is parallel to the longest direction of the volume (Figure 5.46).

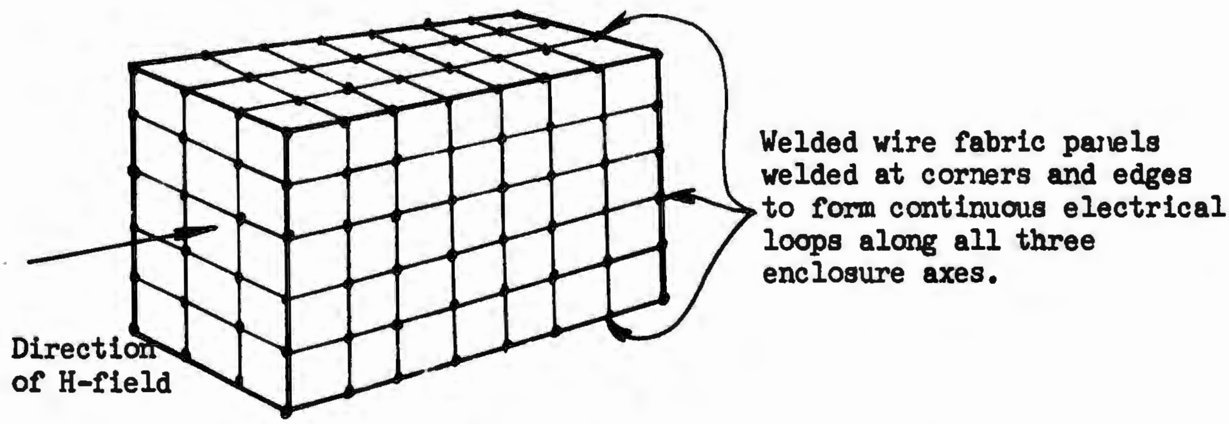


FIGURE 5.46 "Worst Case" H-field Orientation for a Volume Shielded with Welded Wire Fabric

An improvement in shielding (an increase in attenuation) can be effected by using inner and outer courses of welded wire fabric in the building construction, as described in Section 5.3.5.2. This increase can be evaluated using calculation techniques given in Section 5.3.5.3.

EMP field attenuation, using welded wire fabric for shielding, is influenced by a number of factors, including:

1. Orientation of structure with respect to the incident H-field. For design purposes, "worst case" orientation is usually assumed.
2. Single course or double course construction.
3. Building or room dimensions.
4. Wire diameter and mesh size (spacing).
5. Wire conductivity and permeability.
6. Proximity to ceiling, walls, or floors containing welded wire fabric.
7. Sizes of openings and penetrations.

8. Quality of workmanship in the construction of the shield, openings, and penetrations.

The following subsections will cover the construction practices and techniques of evaluating welded wire fabric shielding, taking the above factors into account.

5.3.5.2 Construction Practices for Welded Wire Fabric Shielding

For welded wire fabric to function properly in EMP shielding applications, required construction practices are as follows:

1. The welded wire fabric shall form electrically continuous surfaces completely enclosing the building or equipment room to be shielded, except for necessary penetrations and openings; details concerning these are covered in requirement 4., below.
2. Junctures of shielding surfaces shall be made in conformity with the techniques shown in Figure 5.47.
3. In situations where a double (inner and outer) course of welded wire fabric shielding is to be installed, the inner and outer cages shall be constructed in conformity with requirements 1 and 2 above. For optimum shielding effectiveness, these cages should be physically as far apart as possible; however, the shielding will not be appreciably degraded if they make random contact electrically.
4. At openings for doorways, ducts, plenums, etc. in a structure shielded with welded wire fabric, all wires around the opening shall be welded to a metal strip encasing the opening, as shown in Figure 5.48.
5. Metal utility piping and electrical conduits entering a welded wire fabric shielded structure from outside shall be connected to the building grounding system at the point of entrance as shown in Figures 5.10, 5.11, and 5.15.

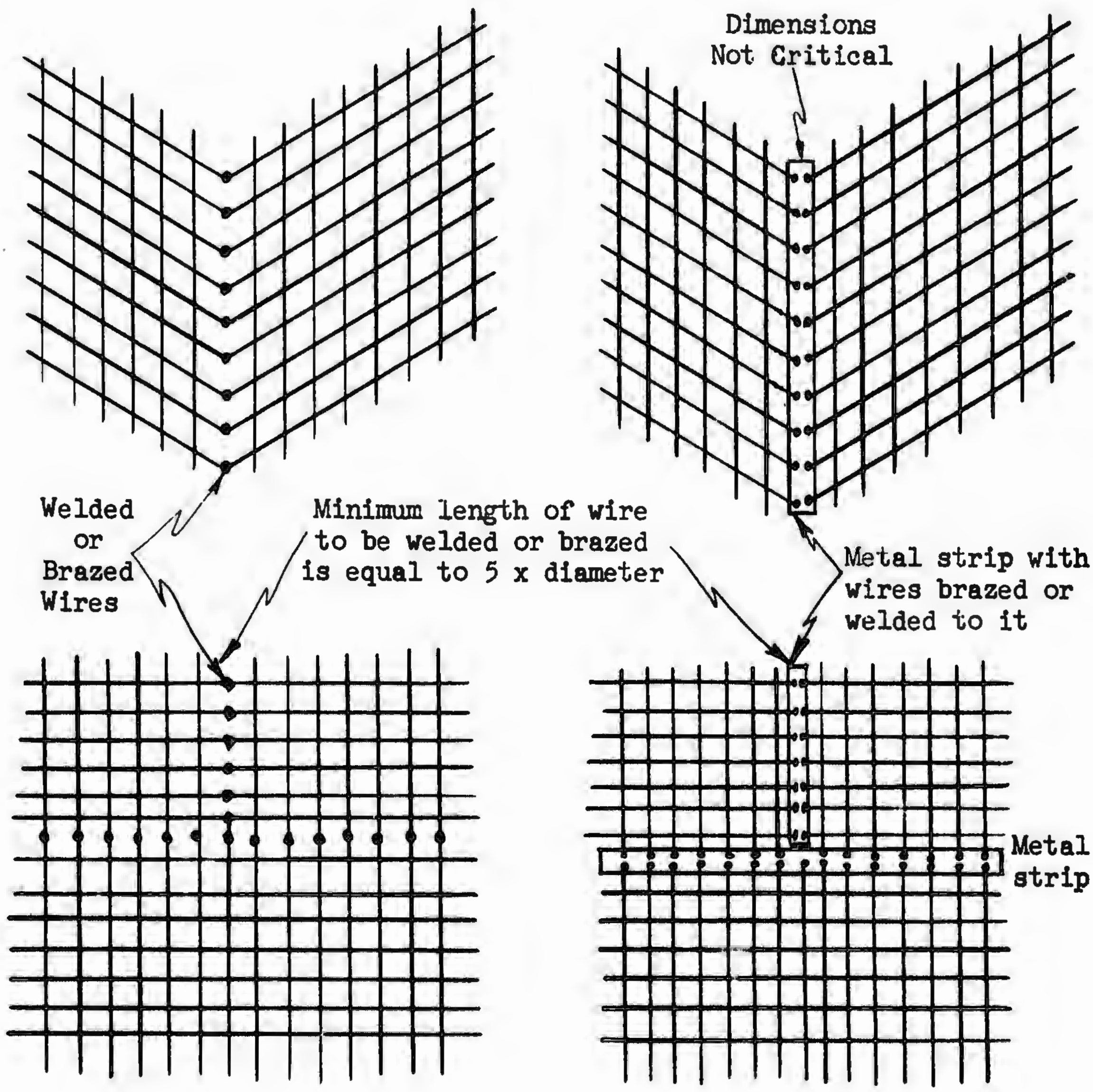


FIGURE 5.47 Welded Wire Fabric Connections

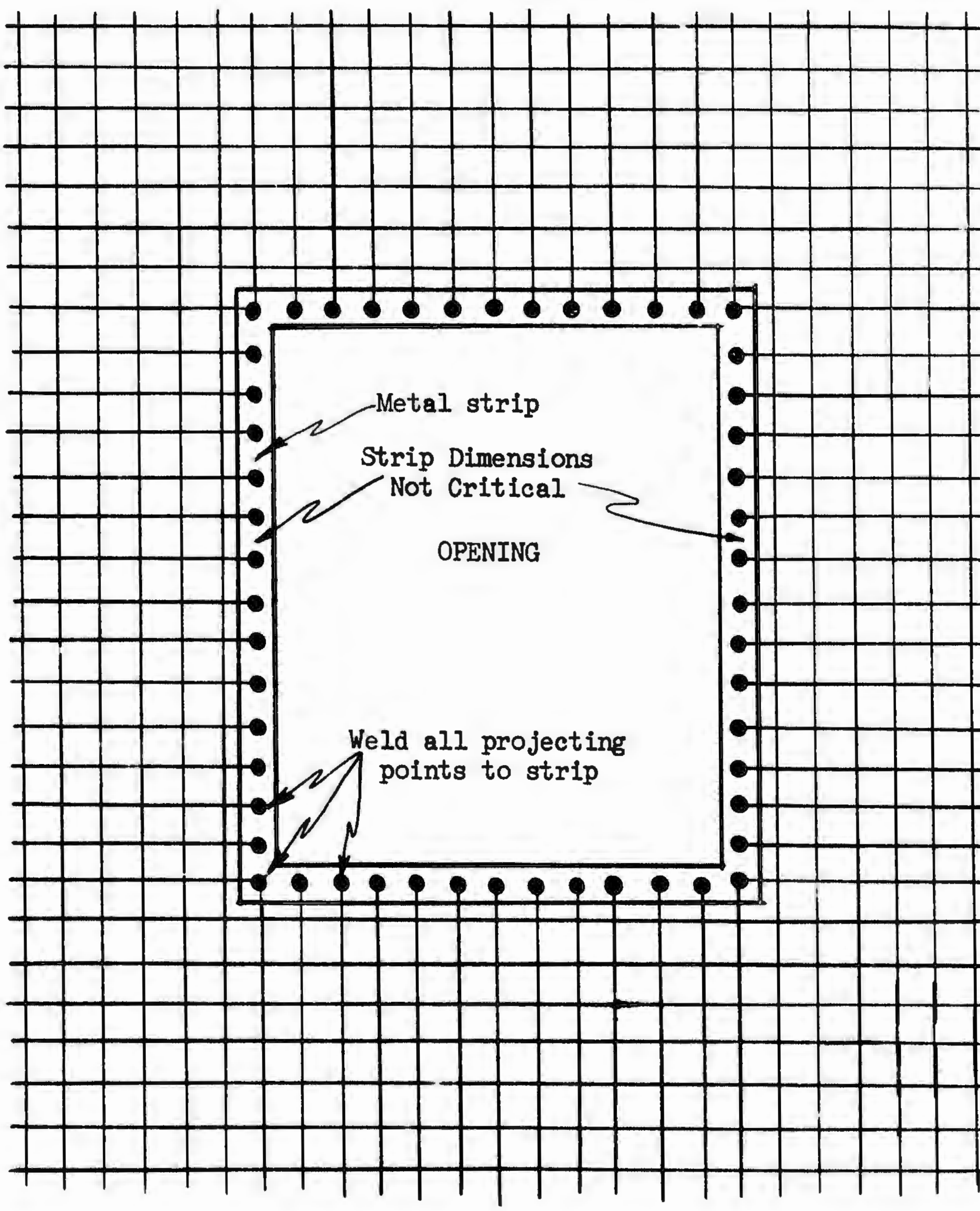


FIGURE 5.48 Termination of Welded Wire Fabric at an Opening

5.3.5.3 Attenuation Calculations for Welded Wire Fabric Shielding

This section covers methods of evaluating the H-field attenuation provided by welded wire fabric, including the effects of penetrations and openings.

In evaluating welded wire fabric as a shielding medium, it will be assumed that the construction conforms to the requirements of Section 5.3.5.2 and that the structure or enclosure to be shielded has "worst case" orientation with respect to the incident H-field.

As was the case with rebar shielding, the effectiveness of welded wire fabric is influenced by structure dimensions and proportions as well as the wire and mesh size and the kind of material used. Subsection 5.3.5.3.1 contains graphs and examples for determining the center-volume attenuation within a building or room having dimensions and proportions within specified practical limits when shielded with a standard diameter and mesh size of steel welded wire fabric. This subsection also contains application factors to evaluate the attenuation when other mesh sizes of single or double course shielding are used. Subsection 5.3.5.3.2 gives the general equations and graphs for determining attenuation where wide variations occur in structure dimensions and proportions, welded wire diameter and mesh size, and the conductivity and permeability of the fabric material.

To simplify the computations, it is assumed that once a particular kind of welded wire fabric has been selected for shielding, it will be applied to all surfaces of the shielded volume.

5.3.5.3.1 Welded Wire Fabric Shielding Calculations, Assuming Definite Values of Conductivity and Permeability

The center-volume shielding attenuation obtained by enclosing a building or room in welded wire fabric can be found from the curves of Figures 5.49 and 5.50. These curves were derived for an assumed wire conductivity of $\sigma_o = 6.5 \times 10^6$ mho/meter and an assumed relative permeability of $\mu_r = 50$, but are valid for a conductivity range of 4.0×10^6 mho/meter to 8.0×10^6 mho/meter and a relative permeability range of 10 to 100.

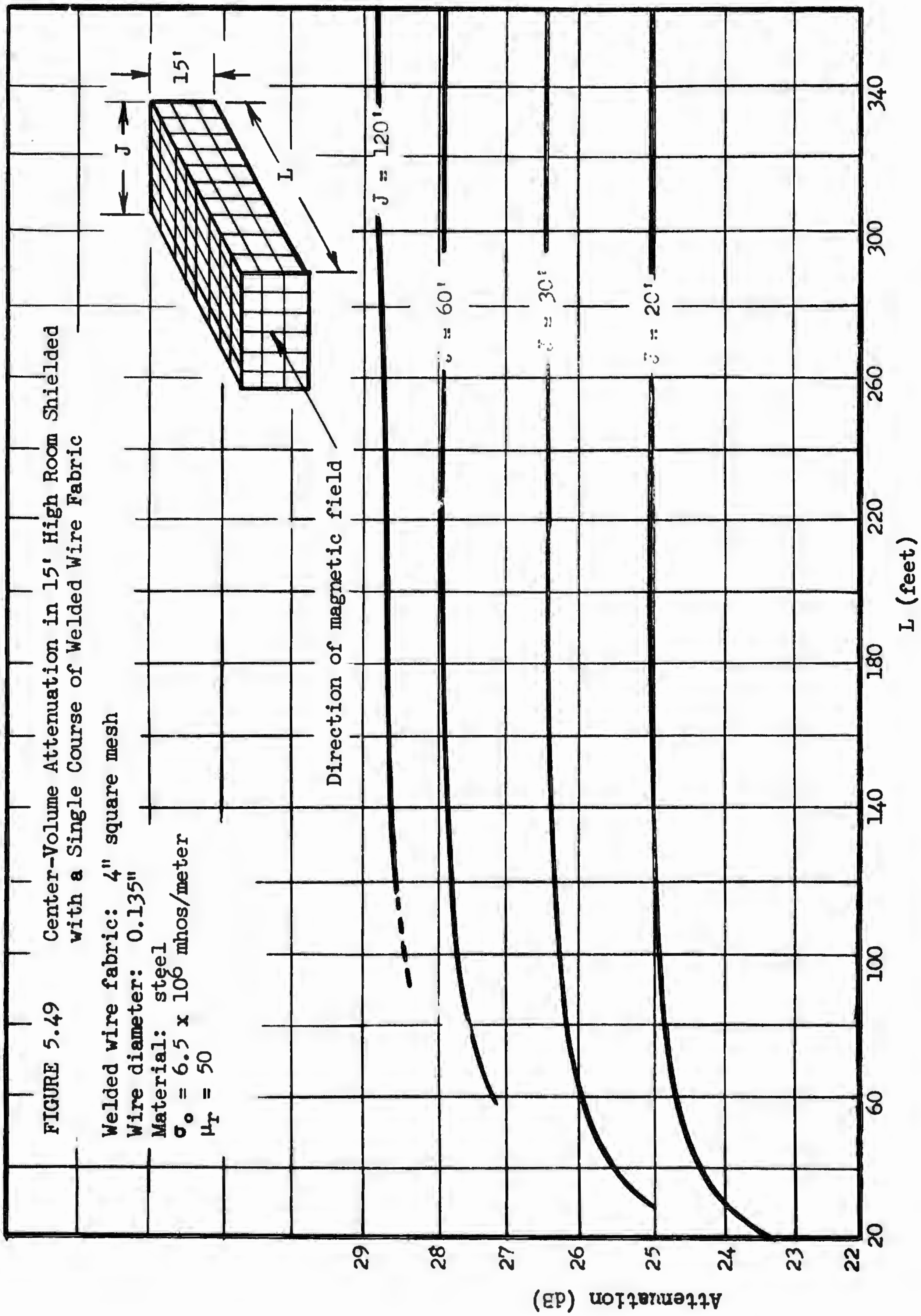
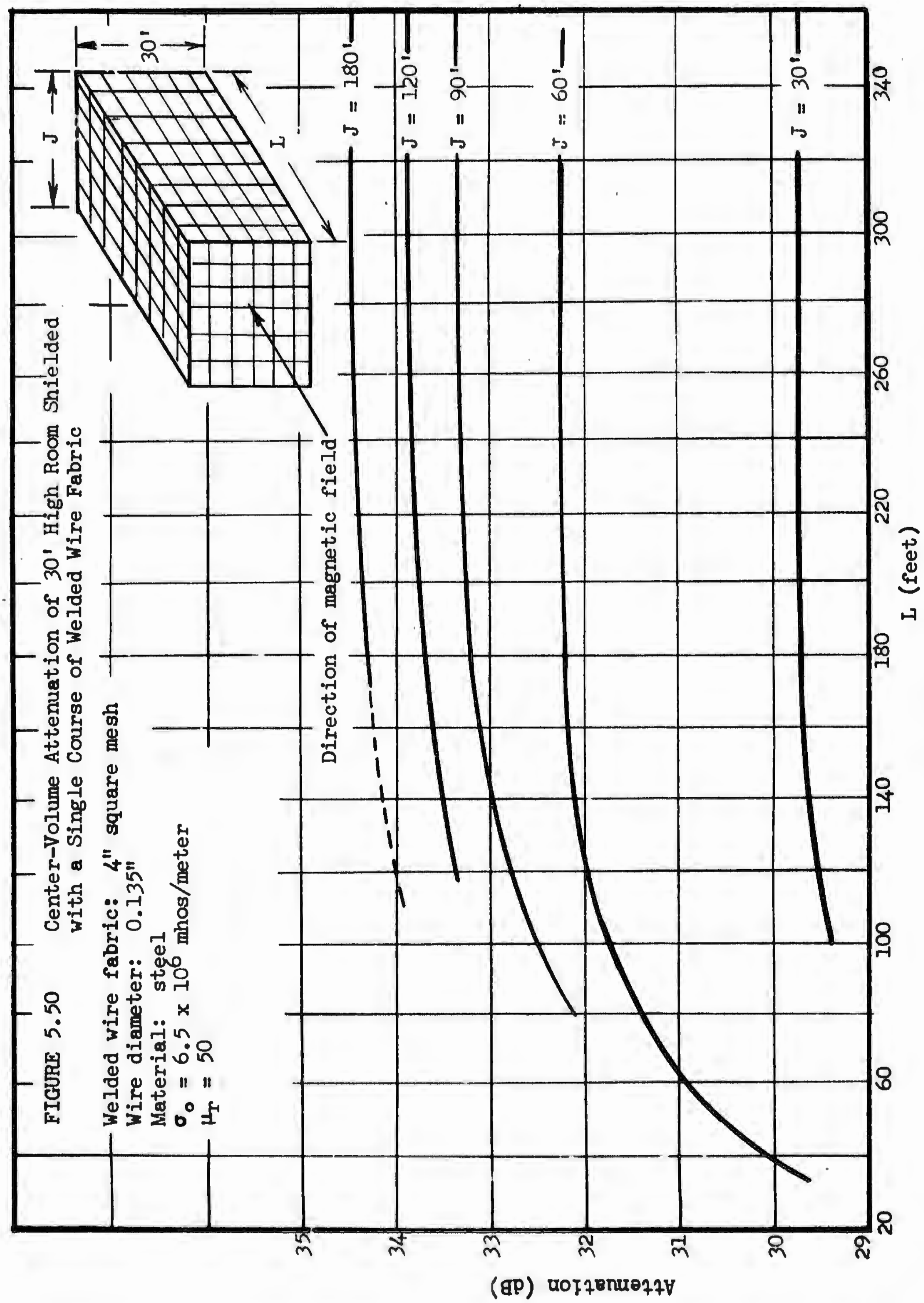


FIGURE 5.49 Center-Volume Attenuation in 15' High Room Shielded with a Single Course of Welded Wire Fabric

FIGURE 5.50 Center-Volume Attenuation of 30' High Room Shielded with a Single Course of Welded Wire Fabric

Welded wire fabric: 4" square mesh
Wire diameter: 0.135"
Material: steel
$\sigma_o = 6.5 \times 10^6$ mhos/meter
$\mu_r = 50$



In Figure 5.49, the height of the shielded volume has been assumed to be 15 feet and in Figure 5.50, 30 feet. Width and length dimensions may vary over a 5 to 1 range.

For various structure proportions, use the following criteria for curve selection:

1. Height 15 feet to 24 feet, use curves for 15 feet. (Figure 5.49)
2. Height 24 feet to over 30 feet, use curves for 30 feet. (Figure 5.50)
3. For variations of the width (J) dimension, use curve equal to or less than the value.
4. For dimensions smaller than the graphs provide, use Subsection 5.3.5.3.2 as the basis for shielding calculations.

The curves of Figures 5.49 and 5.50 are valid only for a single course of 0.135 inch diameter welded wire fabric of four inch mesh size. Applicable correction factors listed in Table 5.3 are used to evaluate shielding attenuations for several other standard mesh sizes and for single course as well as double course welded wire fabric construction.

TABLE 5.3

APPLICABLE ATTENUATION CORRECTION FACTORS FOR WELDED WIRE FABRIC SHIELDING

Type of Configuration and Parameters			Attenuation Increment
Wire Diameter inches	Mesh Size inches	Construction	Δ dB
0.135	6	Single course	- 4
0.135	4	Single course	0*
0.135	3	Single course	+ 3
0.135	2	Single course	+ 6.5
0.135	6**	Double course	+ 3
0.135	4**	Double course	+ 6.5

Continued . . . . .

Table 5.3 (cont.)

* No dB corrections are necessary for a single course of four inch mesh, 0.135 inch diameter welded wire fabric, because this was the basis for Figures 5.49 and 5.50.

** For double course of welded wire fabric of six inch or four inch mesh, 0.135 inch diameter, use the increment for single course, three inch or two inch mesh, 0.135 inch diameter wire.

The attenuation value for the applicable room or building height is found on Figure 5.49 or Figure 5.50. For welded wire fabric other than four inch square mesh and/or for double course construction, it will be necessary to apply a correction increment (± Δ dB listed in Table 5.3) to obtain the attenuation. It should be noted that the corrected value applies only to the center portion of the shielded volume. There will usually be less attenuation (more degradation of shielding) with increasing proximity to shielding surfaces. Figure 5.51 shows the increase in degradation versus distances from ceilings, walls, or floors shielded by welded wire fabric; this is applicable to buildings of heights ranging from 15 feet to 45 feet and lengths ranging from 45 feet to 300 feet. Degradation values in Figure 5.51 must be subtracted from the corrected center-volume attenuation as determined above to find attenuations within five feet of a ceiling, wall, or floor.

When welded wire fabric is embedded in the outside surface of a wall, there will be appreciable wall thickness between the fabric and equipment placed against an inside wall. This must be considered in the calculation and added to the physical distance between the shielding and the equipment. In double course welded wire fabric construction, the inner course will be comparatively close to equipment against an inside wall. In this case the additional attenuation afforded by the double course construction will be offset by reduced attenuation in proximity to the inner course of welded wire fabric shielding. However, equipment placed six feet or further from the wall would benefit fully from the double course shielding.

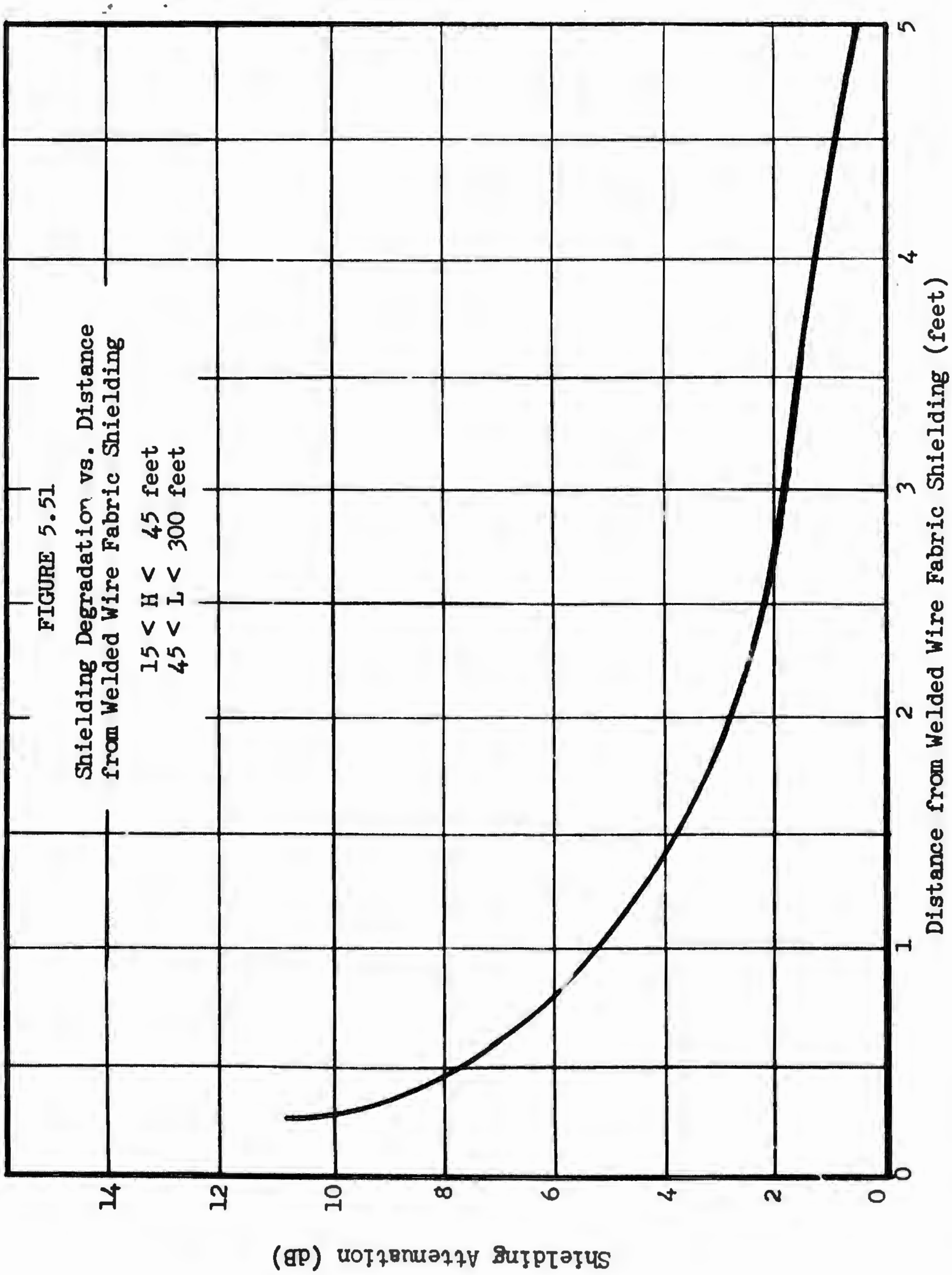


FIGURE 5.51
Shielding Degradation vs. Distance from Welded Wire Fabric Shielding

Sample calculations of attenuation are given in the following examples:

Example 1: Single Course Welded Wire Fabric Construction

Given	Building Height (H)	=	18 feet
	Building Width (J)	=	32 feet
	Building Length (L)	=	145 feet

Assume that the welded wire fabric is 0.135 inch diameter steel with a six inch square mesh and that material conductivity (σ_o) and permeability (μ_r) are within the ranges for which Figures 5.49 and 5.50 are valid.

Since H = 18 feet, use Figure 5.49 for H = 15 feet. On curve for J = 30 feet and L = 145 feet, read center-volume attenuation of 26.3 dB. From Table 5.3, apply the applicable correction factor Δ dB = - 4 dB for six inch square mesh fabric applied single course. Attenuation at the center of the shielded volume is then 26.3 - 4 = 22.3 dB. This will be the attenuation in the shielded building farther than six feet from shielding surfaces.

Assume that the welded wire fabric is embedded in an outside wall and that the wall thickness between the inside of the building and the shielding is a minimum of 22 inches (1.83 feet). Equipment against this wall would be subject to a shielding degradation of approximately 3 dB, as indicated in Figure 5.51. The net attenuation for equipment at the wall would then be 22.3 - 3 = 19.3 dB.

Example 2: Double Course Welded Wire Fabric Construction

If a double course of welded wire fabric is used for shielding the building of Example 1, the center-volume attenuation would be:

26.3 dB	from Figure 5.49
+ 3.0 dB	from Table 5.3
29.3 dB	

For equipment against an inside wall, assuming that the inner course of welded wire fabric is embedded three inches from an interior surface, the degradation from Figure 5.51 would be 10 dB or -10 dB attenuation. Therefore, the net attenuation for equipment at the wall would be 29.3 - 10 = 19.3 dB.

Openings and penetrations in welded wire fabric shielding will degrade its effectiveness, resulting in reduced attenuation in the vicinity of such openings. Figure 5.27 shows how openings are defined in terms of two dimensions: the dimension of the opening (W) in the direction of the horizontal H-field and the distance within the shielded area from the opening (Y). Figure 5.28 shows how much attenuation can be expected as (Y) varies with respect to (W). This graph can be used to determine the values of attenuation at varying distances from a known size opening or to find the maximum permissible width of an opening if equipment is to be placed at some known distance from the opening, assuming an attenuation that is to be maintained; or it can be used to find the clearance that must exist from a given width opening to attain some specified amount of attenuation.

An example of evaluating the attenuation caused by an opening follows.

<u>Example 3</u>: Single Course Welded Wire Fabric Shielding
with a Doorway Opening 8 ft. x 3 ft.

From Example 1 it was determined that a particular building shielded with six inch square mesh welded wire fabric had a center-volume attenuation of 22.3 dB. It will be assumed that a doorway into the building is eight feet high and three feet wide.

The opening dimension (W) in the direction of the horizontal H-field is then the doorway width of three feet. Refer to Figure 5.28 and from the curve that becomes asymptotic to the center-volume attenuation (22.3 dB), read the ratio Y/W. This is approximately three, which means that a distance Y = 3 x W = 3 x 3 = 9 feet inside the room, the attenuation will be the same as in the center of the room. For equipment inside the doorway, but less than nine feet from it, the attenuation will be less than the 22.3 dB level.

When the shielding effectiveness of a particular room with openings must be maintained at some desired attenuation level (approaching, but not exceeding the center-volume value), wave guides (metal sleeves) as shown in Figure 5.29 can be installed in openings. It will be assumed that an attenuation of 20 dB must be present throughout the shielded volume. To determine

the distance from the wall which would maintain a 20 dB attenuation level, proceed as follows: From Figure 5.51 it can be determined that the net attenuation due to proximity to shielding surfaces would not be degraded more than 22.3 - 20 = 2.3 dB provided no equipment were placed closer than about 2-1/2 feet from a shielding surface.

Example 4:

Assume a 3' x 8' wave guide type opening is desired in a rebar shielded area having a center-volume attenuation of 20 dB. Enter the graph on Figure 5.30 and at the 20 dB level read a Y/W ratio of 1. The length of the wave guide must be Y = W x 1 = 8' x 1 = 8 feet, where W is the largest dimension of the opening.

5.3.5.3.2 Attenuation Calculations for Welded Wire Fabric Considering Variations in Wire Diameter, Mesh, Conductivity, and Permeability - for any size structure

The shielding calculation methods outlined in this section can be applied to any size structure and also in those cases where variations in welded wire fabric conductivity, permeability, diameter and/or mesh size preclude use of the graphical methods described in Section 5.3.5.3.1.

These formal attenuation calculation methods will require certain basic information as to room or building size and knowledge of the welded wire fabric parameters, as follows:

H = height of room or building in meters
J = width of room or building in meters
L = length of room or building in meters
μ = permeability of welded wire fabric = $\mu_o \times \mu_r = 4\pi \times 10^{-7} \times \mu_r$
σ_o = conductivity of welded wire fabric in mho/meter
d_o = diameter of welded wire fabric in meters
d = mesh size of welded wire fabric in meters

Briefly, the computation procedure requires the determination from graphs of several factors (K, -A, and B) based on structural proportions. These factors and the basic information above are used to determine two

other constants (X and Y). These constants are used with graphs to find two other factors (U and W), which are then combined with certain given parameters into an attenuation formula. The following steps outline this procedure:

<u>Step 1</u>. Determination of Constant Y

$$Y = \frac{K\,(A + B)}{2}, \quad \text{where}$$

K is found on Figure 5.38 for corresponding values of H/L and H/J (limited to height-to-width proportions between 1:1 and 1:10)

-A is found on Figure 5.42 for the corresponding value of ratio d/d_o

B is found on Figure 5.43 for the corresponding value of ratio L/d.

<u>Step 2</u>. Determination of Constant X

$$X = \frac{10^7 \sqrt{\mu}}{56.6\; d_o \sqrt{\sigma_o}}$$

<u>Step 3</u>. Determination of Factors U and W

Using the values of constants Y and X as calculated in the preceding steps, obtain corresponding values for factors U and W from Figures 5.44 and 5.45 and then change the value of U read from Figure 5.44 from dB to a ratio U_R by formula:

$$U_R = \text{antilog } U/20$$

<u>Step 4</u>. Calculate "Center-Volume" Attenuation

$$\text{Center-Volume Attenuation (dB)} = \left[20 \log \left\{ \frac{13,300}{7.89 \times 10^{-6} \times U_R \times W \times \frac{d(H+J)}{2\,KHJ}} \right\} - 4 \right]$$

The equation above can be used for evaluating the shielding afforded by welded wire fabric applied both single course and double course. Double course welded wire fabric calculations are based on the fact that in the construction of double courses, the mesh size (d) will generally be less than the separation between the two courses. This makes it possible to treat the double course as a single course having half the mesh size.

Thus, to calculate the attenuation provided by a double course of welded wire fabric for shielding volumes outside the range of Figures 5.49 and 5.50, the distance between wires (d) is halved; calculations are then made in the same manner as for a single course of welded wire fabric using the methods described in Sections 5.3.5.3.1 and 5.3.5.3.2.

For either type of welded wire fabric construction, degradation at or near shielding surfaces can be found from Figure 5.51. Then, by applying corrections to the center-volume attenuation found above, the net attenuation can be determined. Likewise, effects of openings and penetrations in double course welded wire fabric shielding are computed as described in Section 5.3.5.3.1.

5.3.6 Commercial EMP Shielding

This section covers the classification, fields of application, construction features and performance criteria for commercial shielding.

Custom-made shielding, capable of providing attenuation of EMP effects, is available from numerous manufacturers such as ACE, Lindgren, Filtron, and Shielding, Inc. Such shielding can be furnished in a variety of configurations for shielding volumes ranging from small room size enclosures to buildings of any reasonable dimensions. (The term "enclosure" connotes the shielded volume.)

Operating principles of commercial shielding are exactly the same as those described in Section 5.3.1.2. Generally, the magnetic attenuation curves or data for shielded rooms show increases in attenuation at frequencies above 10,000 Hz. For "worst case" evaluation, therefore, the value of attenuation at 10,000 Hz can be taken as the magnetic pulse (EMP) attenuation. Then, in all cases the actual value of EMP shielding attenuation will be equal to, or greater than, this value.

5.3.6.1 Construction Details of Commercial Shielding Enclosures

Commercially shielded enclosures are available in three different basic types, as follows:

1. "Single-Shield" construction with only one envelope of shielding surrounding the shielded volume. This is the simplest and least expensive form of commercial shielding. Shielding materials commonly used are single sheets of steel or copper carefully joined together or screening composed of 22 mesh, 15 mil copper wire.
2. "Double-Shield" construction, wherein two separate envelopes of shielding material enclose the shielded space. These envelopes are electrically insulated from each other except for one point of contact where power conduits and other metal utility piping are brought into the shielded volume. This type of construction is the most complicated and costly commercial shielding.
3. "Cell-type" construction, wherein each prefabricated panel of the enclosure is completely enclosed by shielding material to form a cell. The complete enclosure consists of many such cells assembled and tested at the site. In cell-type shielding there is no separation of envelopes. Therefore, it is less complicated to install than "double shielding" and for this reason it is more commonly used than "double shielding". At one time cell-type shielding was considered inferior to double-envelope shielding at the low frequency end of the shielding spectrum; present state-of-the-art evaluations indicate no great difference in performance between the two types.

Utility openings, personnel doorways and penetrations for piping, conduit, air conditioning ducts, wave guides, etc. will adversely affect commercial shielding. The shielding manufacturer, therefore, will generally require working drawings showing the configuration of the shielded volume as well as sizes, kinds and placement of openings and penetrations before engineering the shielding at some specified level.

5.3.6.2 Performance Recommendations for Commercial EMP Shielding

In any application where commercial shielding is contemplated, the

following requirements shall apply:

1. Commercial EMP shielding shall be evaluated by measurement of its ability to attenuate low impedance (magnetic) fields at frequencies of the order of 10,000 Hz and higher, in accordance with the procedures stated in MIL-STD-285 entitled, "Military Standard Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of", latest revision or superseding document(s).
2. Alternatively, equivalent manufacturers attenuation measurements techniques are acceptable provided the actual performance of the shielding will equal or exceed that measured by following MIL-STD-285.
3. Commercially shielded enclosures shall be bonded (by welding if ferrous or brazed if non-ferrous) to the common structural system or internal grounding ring whichever is closer. Large volumes with commercial shielding shall be grounded by bonding at each structural intersection.
4. All penetrations and attachments into commercially shielded rooms shall be constructed in conformity to the criteria requirements of Section 5.3.2.2.

5.3.7 EMP Shielding Afforded by Equipment Cabinets and Junction Boxes

5.3.7.1 Introduction

This section covers metal cabinets used for housing electrical equipment and conduit junction boxes in shielded as well as unshielded areas.

The attenuation afforded by equipment cabinets depends upon the amount of magnetic flux entering through panels, openings between panels and frame, through louvers, and through openings for panel-mounted equipment. Methods of constructing these cabinets and junction boxes and evaluating their attenuation are covered in the sections that follow.

5.3.7.2 Construction Practices for Metal Equipment Cabinets and Junction Boxes

There are two general types of equipment cabinets, those without metal floor plates (open bottom) and those with floor plates (closed bottom). Conduit junction boxes are usually wall or ceiling mounted.

Access panels that are removable are ordinarily bolted to angle iron frames. Ordinarily, if no RFI gaskets are used, irregularities in flatness may result in openings for leakage flux between frame and panel. This will degrade the shielding effectiveness of the equipment cabinet.

Equipment cabinets fitted with conductive panel gaskets could provide an added 20 dB to 25 dB of attenuation. However, to realize this gain all instruments, control devices, relays, etc. mounted on panels may have to be compartmentalized or assembled with wave guide sleeves similar to those used for openings. (Section 5.3.3.3)

To maintain high levels of attenuation within equipment cabinets and junction boxes, required construction practices are as follows:

1. Doors, access and cover panels, wave guides, air vent ducts, and conduits shall make good electrical contact wherever they join the cabinet or box.
2. Mating surfaces of panel joints shall be smooth, highly conductive, and shall be of non-corrosive metals that are similar in the electrochemical series. Anodizing, paint, or other insulating films shall be removed before assembly.
3. All conductors entering or leaving an equipment enclosure or junction box shall be contained in conduit. The conduits shall be welded to the box or enclosure or fastened to it by threaded nipples with metal bushings and locknuts to maintain shielding effectiveness and grounding conductivity. Specific practices for terminating conduits at equipment cabinets are detailed in Figure 5.18. (Section 5.3.2.2)

4. The choice between "open bottom" and "closed bottom" cabinets shall be dictated by attenuation requirements. However, whenever there is any doubt about which type of equipment cabinet to specify, a "closed bottom" cabinet is preferable. The attenuation should, in any case, be evaluated by making the calculations contained in the following section.

5.3.7.3 Equipment Cabinet and Junction Box Attenuation Calculations, including Effects of Cabinet Openings and Penetrations

This section covers attenuation calculations for junction boxes and for equipment cabinets of both open bottom and closed bottom construction and methods of evaluating the effects of openings and penetrations in cabinets of the closed bottom type.

Equipment cabinets without metal floor panels will provide very little attenuation of EMP fields for equipment located near the bottom of the cabinets. For open bottom cabinets without louvers or other panel openings, the reduction in shielding attenuation (degradation) at the bottom will mainly depend upon the longer dimension (W) of the bottom opening. "Worst case" conditions producing the greatest shielding degradation (lowest attenuation) exist when the largest cabinet opening is parallel to the EMP field flux. Cabinet and field orientation which gives this combination should always be assumed. Only horizontal field orientations need be considered.

Figure 5.52 shows how the attenuation of a tightly bolted cabinet (bolt spacing 4" on centers) having metal-to-metal contacting surfaces and an open bottom varies with the Y/W ratio, where Y is the distance from the bottom opening and W is the maximum dimension of the opening (either width or depth). As an example, an equipment cabinet 7 feet high, 3 feet deep, and 2 feet wide but without a metal panel at the bottom will provide an attenuation of about 7 dB one foot above the bottom, attenuations of 16 dB three feet above the bottom, and about 17 dB six feet from the bottom. Any additional openings in the cabinet such as louvers or equipment mounting holes will further reduce these attenuations.

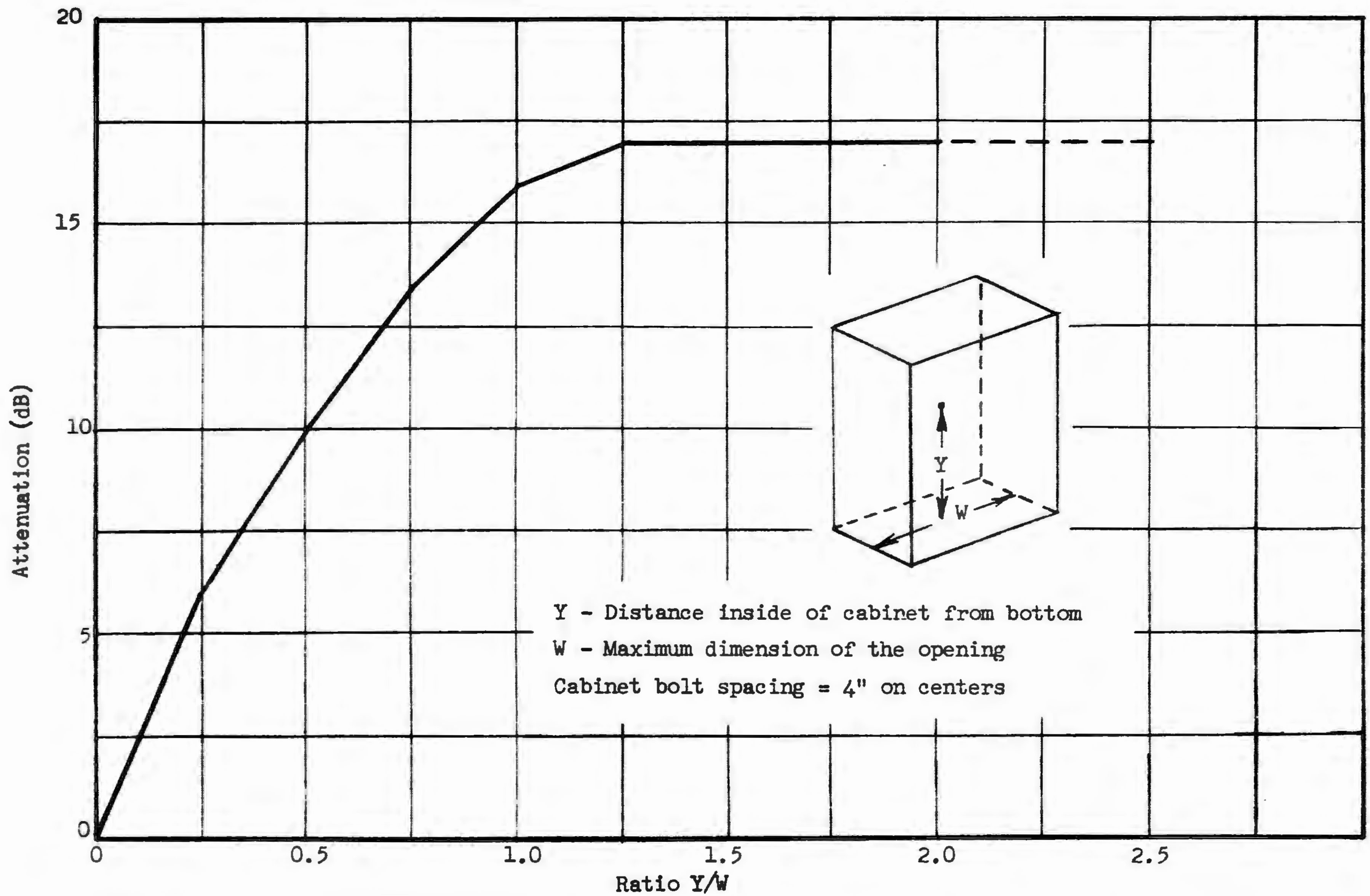


FIGURE 5.52 Attenuation inside a Tightly Bolted Equipment Cabinet with an Open Bottom

The attenuation afforded by completely enclosed junction boxes and by equipment cabinets with tightly bolted-on unlouvered panels, as shown in Figure 5.53, depends principally on leakage around panels and flanged joints and can be calculated as follows:

$$\text{Center Volume Attenuation (dB)} = 20 \log 750 \left[\frac{\dfrac{0.04\ MN}{S} + \dfrac{0.8\ \pi\ NP}{100\ R}}{900\ Q} \right]$$

where Q = dimension of panel edge along opening parallel to the direction of the horizontal magnetic field in centimeters.

P = dimension of panel edge along opening perpendicular to the direction of the magnetic field in centimeters.

N = dimension of enclosure perpendicular to the plane of the panel in centimeters.

M = total width of angle iron flange to which the panel is attached (assuming panel overlaps full width of flange) in centimeters. Total width used in sample calculations is one inch for each flange or M/2 + M/2 = M = 5.08 cm.

S = average gap between panels and flange in centimeters. Average width used in calculations S = 0.16 cm.

R = effective resistance to circulating current along one face of the opening, through the screws and contacting surfaces and along the other face in ohms. A typical value of R, used in the calculations, is R = 0.01 ohm.

By substituting the given values of W, S, and R into the equation, the following is obtained:

$$\text{Center Volume Attenuation (dB)} = 20 \log 750 \left[\frac{1.27\ N + 2.512\ NP}{900\ Q} \right]$$

The 1.27 N term is infinitesimal compared to the 2.512 NP term. Therefore, the equation will reduce to (approximately):

$$\text{Center Volume Attenuation (dB)} \approx 20 \log \left[2.1 \frac{NP}{Q} \right]$$

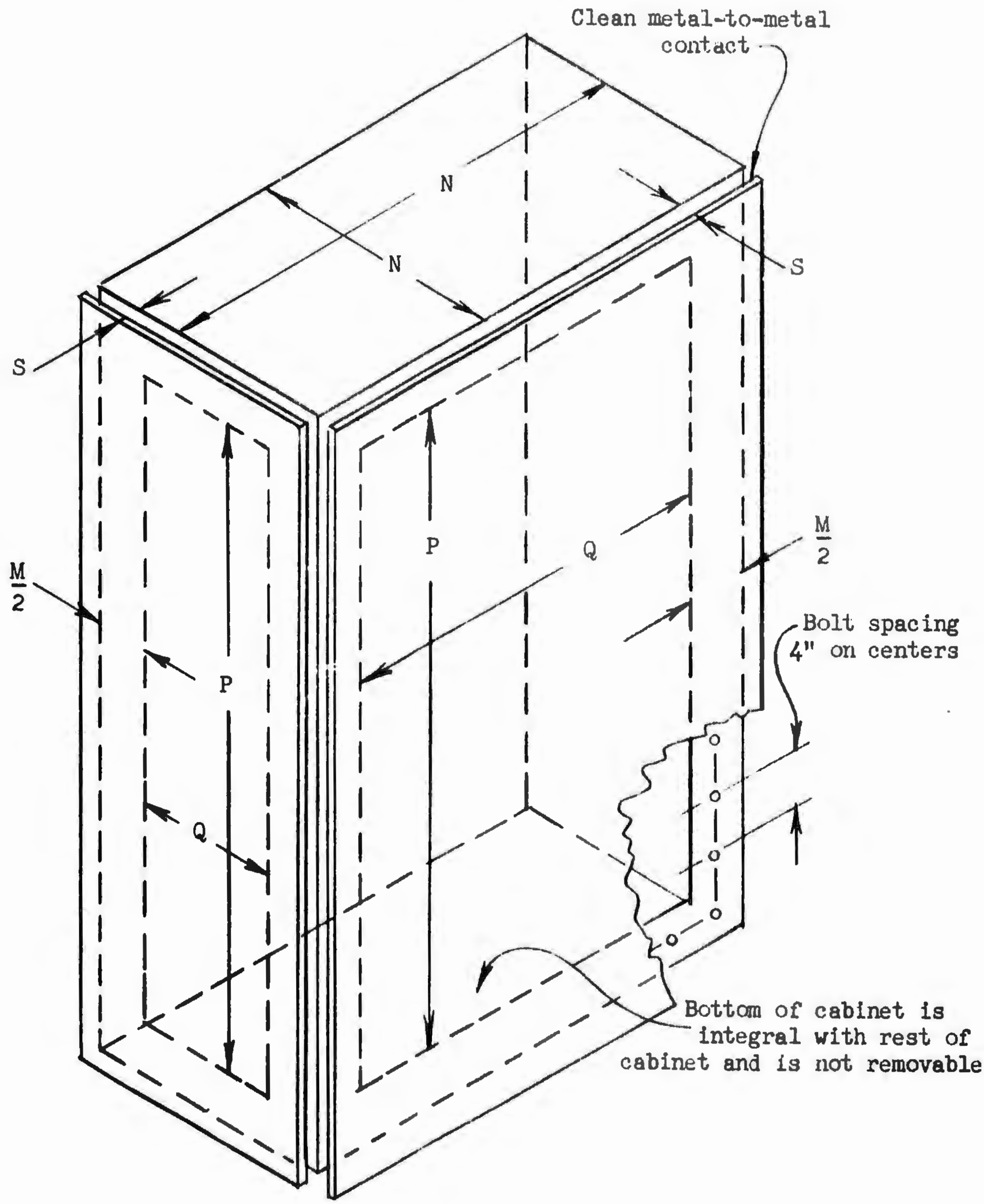


FIGURE 5.53 Dimensions and Orientation of Closed Bottom Equipment Cabinet

A sample calculation of attenuation afforded by a completely closed equipment cabinet having four tightly bolted side panels (4" bolt spacing) and welded top and bottom panels is given in the following example.

Example 1:

Assume that the equipment cabinet in Figure 5.53 has the following dimensions:

Width = 30 inches

Depth = 60 inches

Height = 90 inches

The lowest attenuation is obtained from a "worst case" horizontal H-field direction which is parallel to the 60 inch dimension. Assume for these calculations that the W, S, and R factors have typical values as given previously.

For this example, $Q = 60$ inches

$P = 90$ inches

$N = 30$ inches

$$\text{Center Volume Attenuation (dB)} \approx 20 \log \left[2.1 \frac{NP}{Q} \right]$$

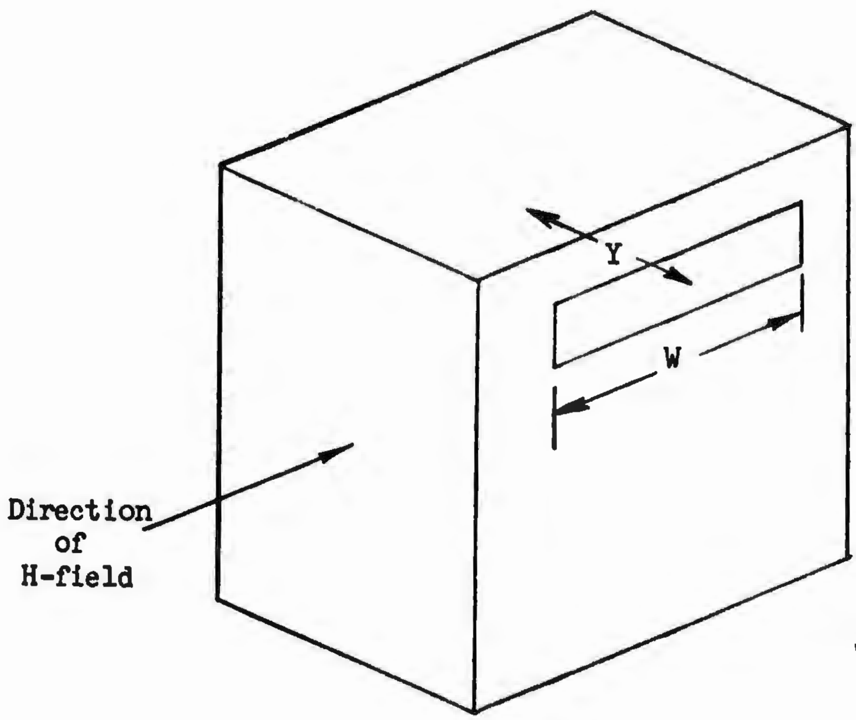
$$\approx 20 \log \left[\frac{2.1 \times 30 \times 90 \times (2.54)^2}{60 \times 2.54} \right]$$

$$\approx 20 \log 240$$

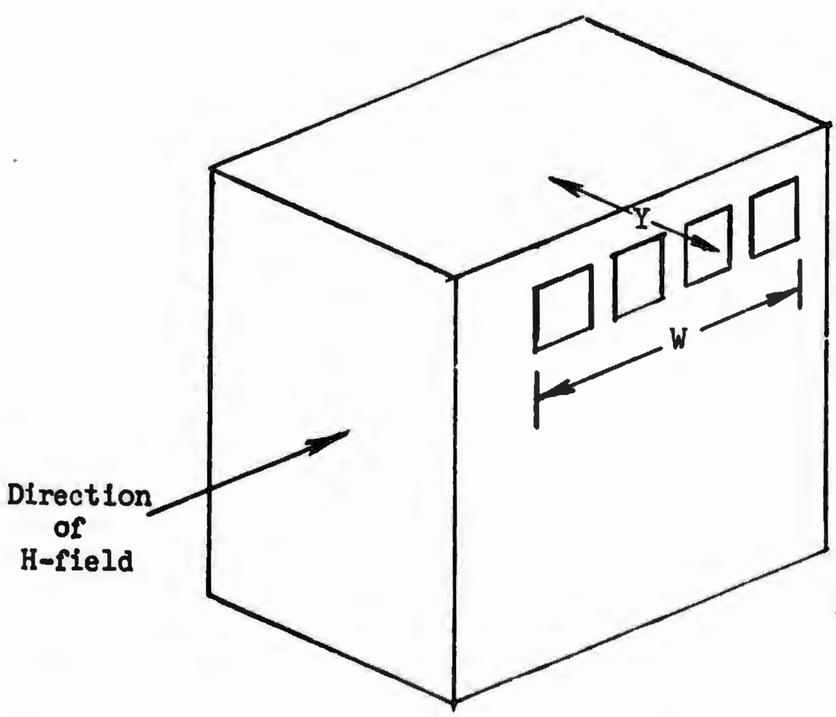
$$\approx 47.6 \text{ dB}$$

The mounting holes for instruments and control devices in metal equipment cabinets have the same adverse effects upon shielding performance of the cabinets as the openings in other forms of EMP shielding. (Sections 5.3.1, 5.3.2, 5.3.4, 5.3.5, and 5.3.6)

In analyzing the effects of various openings that may be grouped on a cabinet panel, the arrangement of the openings must be considered. The upper diagram of Figure 5.54 shows a single opening with a dimension (not a diagonal) of (W) parallel to ι H-field direction. The dimension (Y), which is variable, represents the distance that a piece of equipment



Single Opening



Multiple Openings

FIGURE 5.54 Dimensions for Openings in Equipment Cabinets

susceptible to an EMP field is placed from the opening in the panel. The lower diagram of Figure 5.54 shows a group of four openings with dimension (W) taken as the dimension of the opening, because the multiple openings shown by this diagram would be considered as one opening when the distance between mounting holes is less than half the corresponding dimension of the opening. If these openings had been arranged in a vertical configuration, dimension (W) would have also been measured horizontally because of the horizontal H-field. Again, dimension (Y) is the variable distance behind the opening. The attenuation within the equipment cabinet behind these openings can be determined by using the graph, Figure 5.28 of Section 5.3.3.3. Attenuation will increase as dimension (Y) increases and will approach, but can never exceed, the center-cabinet attenuation calculated as above.

Example 2:

Assume now that a six inch vertical by eight inch horizontal opening is necessary in the 30 inch panel. "Worst case" field orientation for this opening is parallel to the opening. The calculated center volume attenuation of the enclosure for this H-field orientation is higher than that just calculated in Example 1, as shown below.

For H-field parallel to opening in 30 inch panel, the following dimensions apply:

$$Q = 30 \text{ inches}$$
$$P = 90 \text{ inches}$$
$$N = 60 \text{ inches}$$

$$\text{Center Volume Attenuation (dB)} \approx 20 \log \left[2.1 \frac{NP}{Q}\right]$$
$$\approx 20 \log \left[\frac{2.1 \times 60 \times 90 \times (2.54)^2}{30 \times 2.54}\right]$$
$$\approx 20 \log 955$$
$$\approx 59.6 \text{ dB}$$

To obtain conservative design data for openings in cabinets, use the center

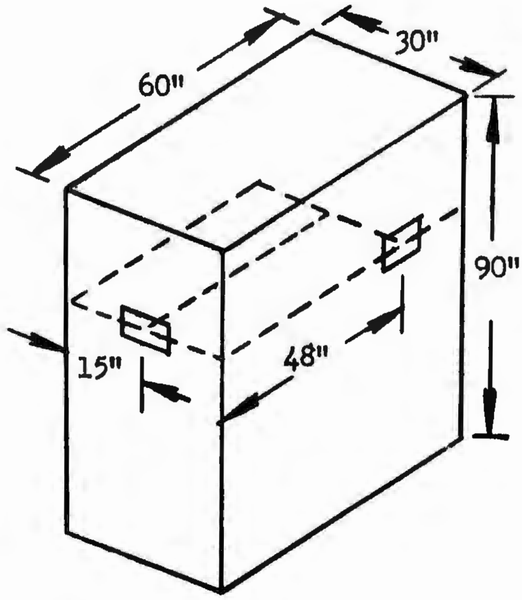
volume attenuation as calculated for "worst case" field orientation for the enclosures. Therefore, the lowest center volume attenuation is used for opening calculations regardless of where the opening is located.

To determine the attenuation at various distances behind the opening in the 30 inch panel, refer to Figure 5.28. At eight inches behind the eight inch opening, Y/W = 1. Sketch on the graph a new curve which is asymptotic at the lowest calculated "worst case" center volume attenuation of the enclosure (47.6 dB). A Y/W of 1 on this curve results in an attenuation of about 21 dB. At 16 inches behind the opening Y/W = 2. The attenuation at 16 inches behind the opening is about 32 dB. At a Y/W of 6 which is 48 inches behind the opening, the attenuation is the same as that calculated for center volume.

Now assume the same size opening was placed in the 60 inch panel instead of the 30 inch panel. The maximum Y distance is 30 inches which results in a maximum Y/W ratio of 30/8 = 3.75. At a Y/ W of 3.75 on the 47.6 dB curve which still applies, the attenuation against the wall opposite the opening is only 43 dB. This means that the calculated center volume of 47.6 dB cannot be reached for this size opening. The 43 dB value establishes a new curve which must be used to obtain attenuation values behind the opening.

The evaluation procedure is as follows. Sketch a new curve on Figure 5.28 which is asymptotic at 43 dB. Use this curve to establish the attenuation levels at various distances behind the 8 inch opening in the 60 inch panel.

Assume now that two openings are required, one in the center of the 30 inch panel and one in the 60 inch panel. Both are to be 6 inches vertical and 8 inches horizontal and both openings are in the same horizontal plane as shown in the sketch below.



Consider that the vertical centerline of the side panel opening is 48 inches away from the front opening. At 48 inches back from the front opening and with no side panel opening, previous calculations for "worst case" center volume attenuation resulted in 47.6 dB at this point. With the side panel opening also considered, however, the attenuation at this same location is calculated as follows. Refer to Figure 5.28 and for a $Y/W = 15/8 = 1.87$, read on the 43 dB curve a value of 29 dB. The side opening allows a lower attenuation at this point and will, therefore, influence the attenuation levels behind the front opening. To best determine the attenuation profile behind the front opening, plot on a graph the attenuation profile of the front opening as if there were no side opening; that is, from the 47.6 dB curve, Figure 5.28.

Distance Behind Front Opening (inches)	Y/W Ratio	dB
8	1	20
16	2	32
24	3	38.5
32	4	45.5
40	5	47.0
48	6	47.5

The resulting curve is shown in Figure 5.55. Next plot the same attenuation profile as influenced by the side opening hole. One point on this profile has been established; that is, at a point 15 inches back of the side opening which is the same point as 48 inches back of the front opening. The dB level of attenuation is 29 dB. This level of attenuation was established from a Y/W of 1.87 on the 43 dB curve. From this point in the cabinet, considering the side opening only, an increase in attenuation will result as one progresses toward the front of the cabinet. This increase in attenuation can be approximated by obtaining the dB level for (N) number of increases in Y/W ratio on the 43 dB curve, where N varies from 0 to whatever value is necessary to allow interception of the attenuation profile curve of the front panel opening just plotted.

Front Opening		Side Opening		
Distance Behind Opening(inches)	Y/W Ratio	Y/W Ratio	Y/W Ratio plus (N)	(dB) from 43 dB Curve Figure 5.25
48	6	1.87	1.87	29
40	5	1.87	2.87	37
32	4	1.87	3.87	40
24	3	1.87	4.87	42.5

Plot columns (2) and (5) on Figure 5.55. The composite graph, shown by a dashed line, depicts the attenuation profile behind the front opening as influenced by both openings. The volume involved in this profile can be

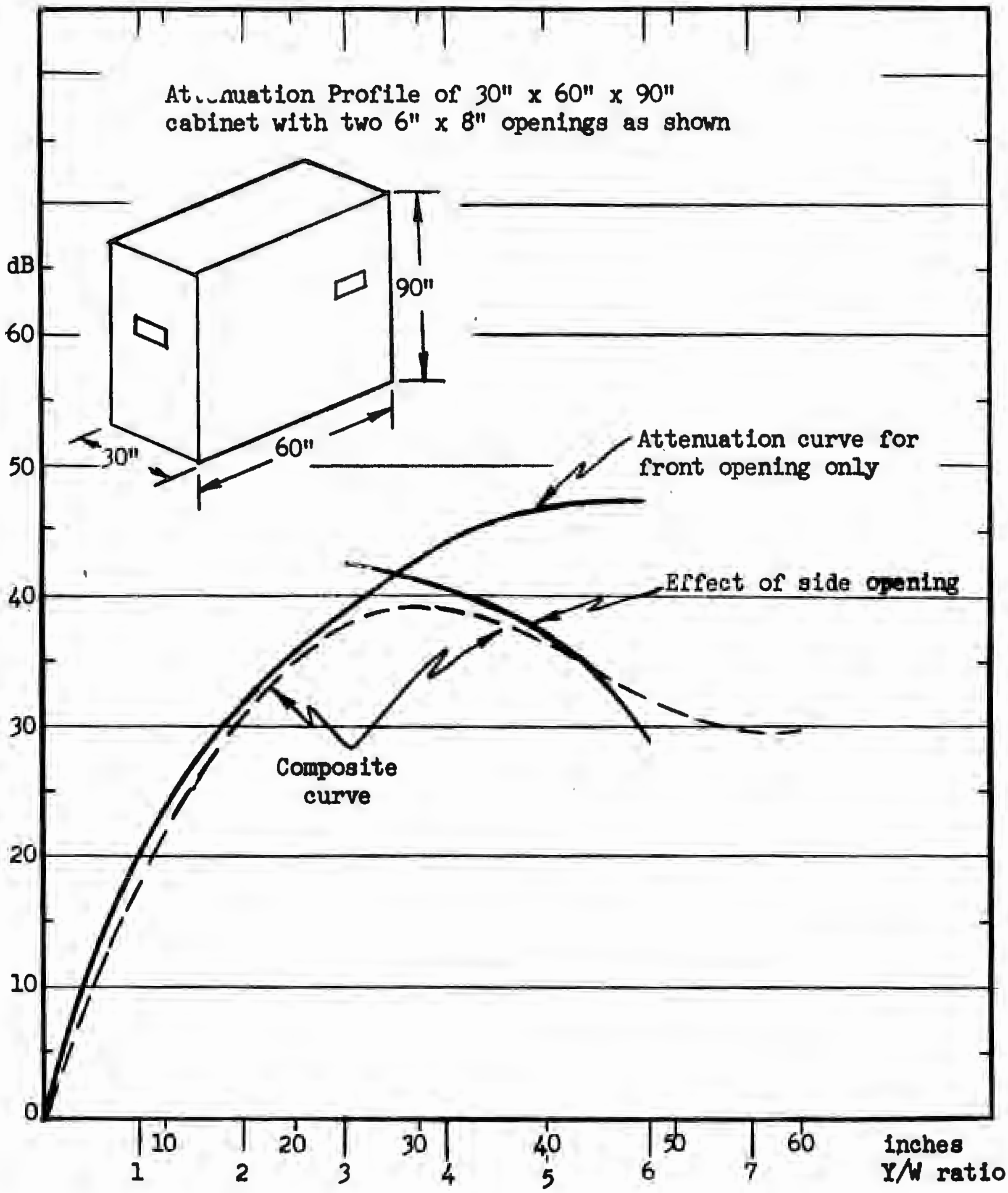


FIGURE 5.55 Attenuation Profile behind Front Panel Opening of a 30" x 60" x 90" Cabinet Containing Two 6" x 8" Openings (see sketch)

considered as one having a frontal area of (6" x 1.5) x (8" x 1.5) and a depth of 60 inches. Above and below this volume, the attenuation will be somewhat higher but can never be higher than 47.6 dB.

From this simple analysis it can be seen that openings can seriously degrade the attenuation of a cabinet. To maintain the attenuation level of the cabinet without openings, some form of wave guide or compartmentalizing technique is necessary.

5.4 Overcurrent and Overvoltage Protection Techniques and Devices

5.4.1 Overcurrent Protection Device Application

In general commercial overcurrent protection devices are either circuit breakers or fuses which operate to open a circuit when the current exceeds a predetermined magnitude and duration or the power flow reverses direction. Because of the operating time characteristics and requirements, such devices will not operate fast enough to be applicable for controlling EMP induced currents. Rather than trying to limit the magnitude and duration of EMP currents induced in power wiring and circuits, a more direct and effective approach is to inhibit these induced currents by enclosing the wiring and circuits within conduits or shielded cables. The EMP induced currents are then harmlessly diverted from cable shields and conduits to the grounding system. Anticipated current magnitudes are such that there will be no heating problems resulting from EMP currents through structure elements, cable shields, or conduits.

It is recommended, therefore, that EMP overcurrent protection for wiring and circuits be achieved by routing all power wiring in shielded cables or in rigid steel conduits. Likewise, all control, instrumentation, and monitoring wiring should be run in rigid steel conduits not smaller than one inch electrical trade size. All conduit mating parts or connections to enclosures must either be welded or threaded. All threaded mating parts that are not welded are coated with an electrically conductive thread compound just prior to assembly.

5.4.2 Overvoltage Protection Device Application

In general, there are three ways to prevent equipment from being damaged or caused to malfunction from overvoltage surges. These are as follows:

1. Keep surges out of the equipment by use of adequate shielding.
2. Improve the tolerance of the equipment to surges.
3. Arrest, clip, clamp, or divert surges that do get onto the system.

In a well-designed overvoltage protection system, all three of these means are employed.

This section deals mainly with the third of these three protection methods: the arresting, clipping, clamping, and diverting of overvoltage surges as ways of increasing the tolerance of equipment to surges. A previous section, Section 5.2.3, included data on shielding schemes for lightning protection; this section is directly concerned with system protection from damage, but not necessarily against malfunctions. For instance, when the control circuitry for a circuit breaker is subjected to a transient overvoltage (surge), the circuit may be permanently damaged and there may also be an undesired circuit breaker operation. The undesired circuit breaker operation would be considered a malfunction. It is quite possible to apply protection techniques which will reduce transient overvoltages to a non-damaging magnitude without reducing them far enough to prevent the malfunction.

Power Plant Performance Specifications cover the maximum permissible magnitudes for transient overvoltages. It is often both undesirable and uneconomical to assume the same specification must be met at all points throughout a power system. Therefore, overvoltage protection techniques generally must be tailored to meet different specifications and requirements at each point of application.

The sections that follow deal with overvoltage protection that is achievable with commercial protective devices for 13.8 kV, 4.16 kV, and

440 volt ac power systems as well as with low voltage control and communication systems. These cover the applications of protective devices in these voltage classes and discuss their capabilities and limitations particularly their applicability to specific jobs. Technical details on the principles of operation of overvoltage protective devices are contained in Section 10.0.

For many years in the electric power industry it has been the practice to require and to demonstrate that many items of electrical equipment be able to withstand surge voltages several times the normal operating voltage of the equipment. The magnitude of such surge voltages has, therefore, been coordinated with the protective abilities of the available lightning arresters. It has been found to be more practical, more reliable, and more economical to coordinate the surge tolerance requirements of the equipment with the protective abilities of the available protective devices than to try to devise a protective scheme for each individual piece of equipment. Ability to meet the required surge tests is usually evaluated in terms of a BIL, or basic impulse insulation level.

As an example, equipment designed for operation on a 13.8 kV power system might be required to be insulated for a BIL of 110 kV. This means that the equipment would have enough insulation to be able to withstand an impulse with a crest voltage of 110 kV having a time to crest of 1.5 microseconds and a decay time to half of crest voltage of 40 microseconds. Such a surge is call a full wave (FW). This particular equipment might also be required to withstand a surge with a crest value of 130 kV which is "chopped" (interrupted by flashover of an auxiliary parallel gap in from 3 to 5 microseconds after the start of the wave). This is called a chopped wave (CW) test. The equipment might also be subjected to and required to withstand a surge that rises to 195 kV in 0.5 microsecond, after which it is chopped to ground by an external gap. This is called a "front-of-wave", or steep-front (SF), test. In addition to these three impulse tests, the equipment might be required to withstand a long duration

switching surge (SS) test, the wave having a crest voltage value 83% of the system 110 kV BIL, or about 91 kV.

A list of nominal system voltages and the corresponding surge test levels to which power equipment might be subjected is shown in Table 5.4. (The 13.8 kV system voltage would be represented by the 14.4 kV nominal system voltage category in this table.) It is important to understand that these are "proof test" withstand voltages for new equipment and not voltages which the equipment could be expected to withstand many times over a period of years.

TABLE 5.4

INDUSTRY STANDARDS FOR TEST LEVELS AND SYSTEM VOLTAGES(1)&(2)

Nominal System Voltage (kV-rms)	Sixty-Cycle 1 minute Test (3) (kV-rms)	Surge Test Levels - kV Crest			Time to Flashover of SF Wave (µs)
		BIL of Full Wave (FW)	Chopped Wave (CW)	Steep Front Wave (4) (SF)	
1.2	10	45	54	75	0.5
2.4	15	60	69	100	0.5
4.8	19	75	88	125	0.5
8.32	26	95	110	165	0.5
14.4	34	110	130	195	0.5
23.0	50	150	175	260	0.5

(1) For oil-immersed transformers rated 500 kVA and above.

(2) From ASA Publication C57.12 - 1956.

(3) This is a test only of insulation.

(4) Not all transformers receive a steep-front test.

The above test levels are industry-wide standards. Different types of power equipment may have different test levels, but these are nearly all covered by industry standards. The intention here is not to review the existing standards for all types of power equipment, but to point out that these standards do exist and that they are routinely followed. The

significant points are:

1. Surge levels are quite high in comparison to the system operating voltage.
2. Surge test levels for equipment are coordinated with the protection abilities of available lightning protective devices. (Insulation levels are reduced only as the protective devices capabilities are improved to maintain the same margins for protection.)

Nothing like the concept of a Basic Impulse Insulation Level (BIL) appears to be used by the electronics industry. Equipment is often designed and built with little or no thought given to providing a reasonable tolerance to surges. When equipment begins to be damaged by surges, the designer is then forced to tailor a protective scheme to an existing piece of hardware. This is generally much less efficient and much more costly than it would have been to initially design sufficient surge tolerance into the equipment.

5.4.2.1 Application of Surge Arresters for Power Circuits

In this section protective measures are presented that will enable a designer to select the proper rating and kind of arresters to protect against overvoltage surges on the power circuits. The basic factor regarding application of surge arresters is to be sure that the ratings of the arresters be chosen so that the normal crest voltage of the system never rises high enough to cause the arrester to sparkover. If this were to happen, the arrester would be subjected to a follow current which it could not interrupt and which it would not have the thermal capacity to withstand. The arrester would in all probability be destroyed and the power circuit faulted.

If no abnormal voltages ever existed on the system, the arresters which are connected from line-to-ground in proximity to the equipment could be chosen on the basis of the line-to-ground or line-to-neutral voltage of the three-phase system. (This is about 58% of the line-to-line system voltage.)

In practice, however, system faults and other transient conditions explained below sometimes cause abnormal voltages to develop and the line-to-ground voltage impressed upon an arrester can be expected to be higher at times than the normal line-to-neutral voltage of the system.

The following excerpt gives concise statements concerning the causes and effects of abnormal voltages and their effects on the selection of surge arresters. It is taken from NEMA Publication LA1 - 1958.

"Abnormal System Voltages":

"Abnormal system voltages may be produced by any of the following causes or by combinations of them:

1. Contact with high voltage circuits.
2. Loss of neutral connection to ground. This can occur by selective operation of circuit-interrupting devices in such a manner as to leave that part of the system on which the arrester is located energized from a power source without grounded neutral.
3. Regulation of apparatus or lines, generator overspeeding following sudden loss of load, hunting by generators or other apparatus, harmonic overvoltages on systems fed by generators without amortisseur windings, restriking in breakers, opening of only one or two poles of three phase breakers, or sectionalizing fuses coincident with a phase-shift of power sources, etc.
4. System faults. Abnormal voltages to ground on systems during faults may vary over a wide range depending on the neutral grounding and system constants. These system characteristics are expressed in terms of the zero sequence resistance R_0; zero sequence reactance X_0; and positive sequence reactance X_1 of the system, including the neutral grounding impedance. From these constants the voltages to ground can be calculated by well known, established methods. The effectiveness of the neutral grounding in limiting the magnitude of line-to-ground voltages may be approximately

expressed in terms of the ratios X_0/X_1 and R_0/X_1. In general, the lower these ratios are, the lower will be voltages to grounds during faults. Consequently, on systems where the ratios are within certain designated limits, lightning arresters whose voltage ratings are less than the system line-to-line voltage may be used; for other designated limits of the ratios, the lightning arresters should have ratings equal to or possibly greater than the system voltage from line-to-line.

"For purposes of selecting the proper arrester voltage rating, three-phase systems may be classified as Type A, Type B, etc. on the basis of the magnitudes of the ratios X_0/X_1 and R_0/X_1. Definitions of each of these types of systems follow:

Type A - neutral grounded systems which are usually well grounded and the reactance and resistance ratios are less than for a Type B system, but the system constants are not known in sufficient detail to establish limiting ratios.

Type B - neutral grounded systems which are "effectively grounded" for which the reactance ratio X_0/X_1 is positive and less than three, and at the same time the resistance ratio R_0/X_1 is positive and less than one at any place on the system.

Type C - grounded neutral systems which do not meet the requirements of the Type B system. Either the reactance ratio of three is exceeded but is still positive, or the resistance ratio of one is exceeded, or both ratios are exceeded.

Type D - isolated neutral systems are the usual ungrounded systems for which the zero sequence reactance is capacitive and the reactance ratio X_0/X_1 is negative and lies between minus 40 and minus infinity.

Type E - isolated neutral systems are those ungrounded neutral systems which do not meet the limits for the Type D isolated neutral systems and which are characterized by a relatively high charging current

or a very high positive sequence reactance. For these the reactance ratio X_0/X_1 is negative and lies between zero and minus 40; over this range partial resonance may occur. Each case must be analyzed and treated upon its own merits."

Table 5.5 summarizes the above selection criteria and establishes a system type corresponding to the particular system neutral operation condition.

Once a system type has been determined from Table 5.5, an appropriate surge arrester voltage rating can be selected from Table 5.6.

For performance evaluation purposes, the protective characteristics of several classes of surge arresters are given in Tables 5.7 and 5.8.

In addition to selecting a surge arrester of the proper voltage rating coordinated with the protection level required for the equipment, the designer should also properly locate the arresters in relationship to the equipment to be protected.

As a general rule, for maximum protection from overvoltages, surge arresters should be installed as close as possible to the equipment they protect. Figure 5.56 is a "one-line" schematic showing the application of surge arresters for hardened and non-hardened loads. Actual physical location of these arresters would be dictated by electrical clearances, proximity to vulnerable equipment such as transformer bushings, etc.

From the standpoint of overvoltage protection, only adequately grounded electrical systems, such as Type A or Type B, should be considered for this installation. However, from an operational viewpoint, these protective measures also encompass the possibility of ungrounded neutral operation if, for tactical reasons, such a system is required.

Examples of the choices of arrester ratings for each type of system follow:

EXAMPLE 1: Class A - Well-Grounded System Neutral

For a 13.8 kV system, if a thorough study of the system indicated

TABLE 5.5

SYSTEM CLASSIFICATION FOR VARIOUS NEUTRAL CONDITIONS

Neutral Condition	Type of System	Limiting Reactance and Resistance Ratios X_o/X_1	R_o/X_1	V/E_n	Abnormal Voltage Ratios V/E	E_a/E_n	Minimum Rating Ratios of Arresters E_a/E
Well grounded	Type A	*	*	*	*	*	*
Effectively grounded	Type B	0 to +3	0 to +1	1.40	0.80	1.40	0.80
Grounded	Type C	+3 to + infinity	1 to + infinity	1.73	1.00	1.73	1.00
Ungrounded (isolated)	Type D	-40 to - infinity	- - -	1.90	1.10	1.90	1.10
Ungrounded (isolated)	Type E	0 to -40	- - -	Each case should be investigated, as partial resonance may occur.			

* Ratios not established, but reactance and resistance are less than for a Type B system.

X_o Zero sequence reactance at any point on system.

X_1 Positive sequence reactance at any point on system.

R_o Zero sequence resistance at any point on system.

V Possible rms maximum abnormal voltage from line-to-ground.

E Maximum rms normal line-to-line system voltage.

E_a Maximum permissible rms voltage rating of arrester to avoid risk of damage during faults.

E_n Maximum rms normal line-to-neutral voltage of system.

TABLE 5.6

MAXIMUM ALLOWABLE SYSTEM VOLTAGE CORRESPONDING TO PREFERRED VOLTAGE RATINGS OF SURGE ARRESTERS

Preferred Arrester Voltage Rating	Maximum Three-Phase System Voltages on which Arresters May Be Used				
	Grounded Neutral Systems of Types as Defined in Text			Isolated Neutral Systems of Types as Defined in Text	
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
volts (rms)	Type A volts (rms)	Type B volts (rms)	Type C volts (rms)	Type D volts (rms)	Type E volts (rms)
175	130/260*	130/260*		Not Applicable	
175	260	220			
650	650	650	650	650	Applies only
1,000	1,000	1,000	1,000	1,000	to long
3,000	4,500	3,750	3,000	2,700-3,000**	transmission
6,000	9,000	7,500	6,000	5,500-6,000**	lines above
9,000	12,800	11,250	9,000	8,200-9,000**	these
10,000	14,500	12,500	10,000	9,000-10,000**	voltage
12,000	15,000	15,000	12,000	11,000-12,000**	classes.
15,000	18,000	18,000	15,000	13,000-15,000**	

* Applies to single phase, 3-wire applications instead of three phase.

** Dual values of voltage are given for the applicable isolated neutral case, Type D. In general, the lower values are recommended since they involve the least risk of abnormal voltages in excess of the arrester rating.

TABLE 5.7

PROTECTIVE CHARACTERISTICS OF STATION-CLASS VALVE-TYPE ARRESTERS

Voltage Rating of Arrester (kV-rms)	Impulse Sparkover Voltage: Rate of Rise of Test Voltage (kV/μsec)	Impulse Sparkover Voltage: kV-Crest Avg.	Impulse Sparkover Voltage: kV-Crest Max.*	Discharge Voltage for 10 x 20 μsec Discharge Current Wave: kV Crest for 5000 Amperes Avg.	kV Crest for 5000 Amperes Max.*	kV Crest for 10000 Amperes Avg.	kV Crest for 10000 Amperes Max.*	kV Crest for 20000 Amperes Avg.	kV Crest for 20000 Amperes Max.*
3	25	11	14	8	9	8	9	9	10
6	50	20	24	15	17	16	19	18	20
9	75	29	35	22	25	24	27	26	30
12	100	38	45	29	33	32	36	36	40
15	125	49	55	36	41	40	45	44	50

* Maximum of the maximum values given in Manufacturers' catalog information on this type of arrester.

TABLE 5.8

PROTECTIVE CHARACTERISTICS OF SECONDARY-CLASS VALVE-TYPE ARRESTERS

Voltage Rating of Arrester (kV-rms)	Impulse Sparkover Voltage: Rate of Rise of Test Voltage (kV/usec)	Impulse Sparkover Voltage: kV Crest Avg.	Impulse Sparkover Voltage: kV Crest Max.*	Discharge Voltage for 10 x 20 μsec Discharge Current Wave: kV Crest for 1500 Amperes Avg.	kV Crest for 1500 Amperes Max.*	kV Crest for 5000 Amperes Avg.	kV Crest for 5000 Amperes Max.*
0.175	10	2.2	3.1	1.5	2.5	1.8	2.8
0.650	10	3.8	6.5	3.5	6.0	4.7	8.5

* Maximum of the maximum values given in manufacturers' catalog information on this type of arrester.

(Impulse performance of arresters shown above is covered by ASA Standard C62.1 - 1962. This is identical to AIEE Standard No. 28 and NEMA Standard LA1 - 1958.)

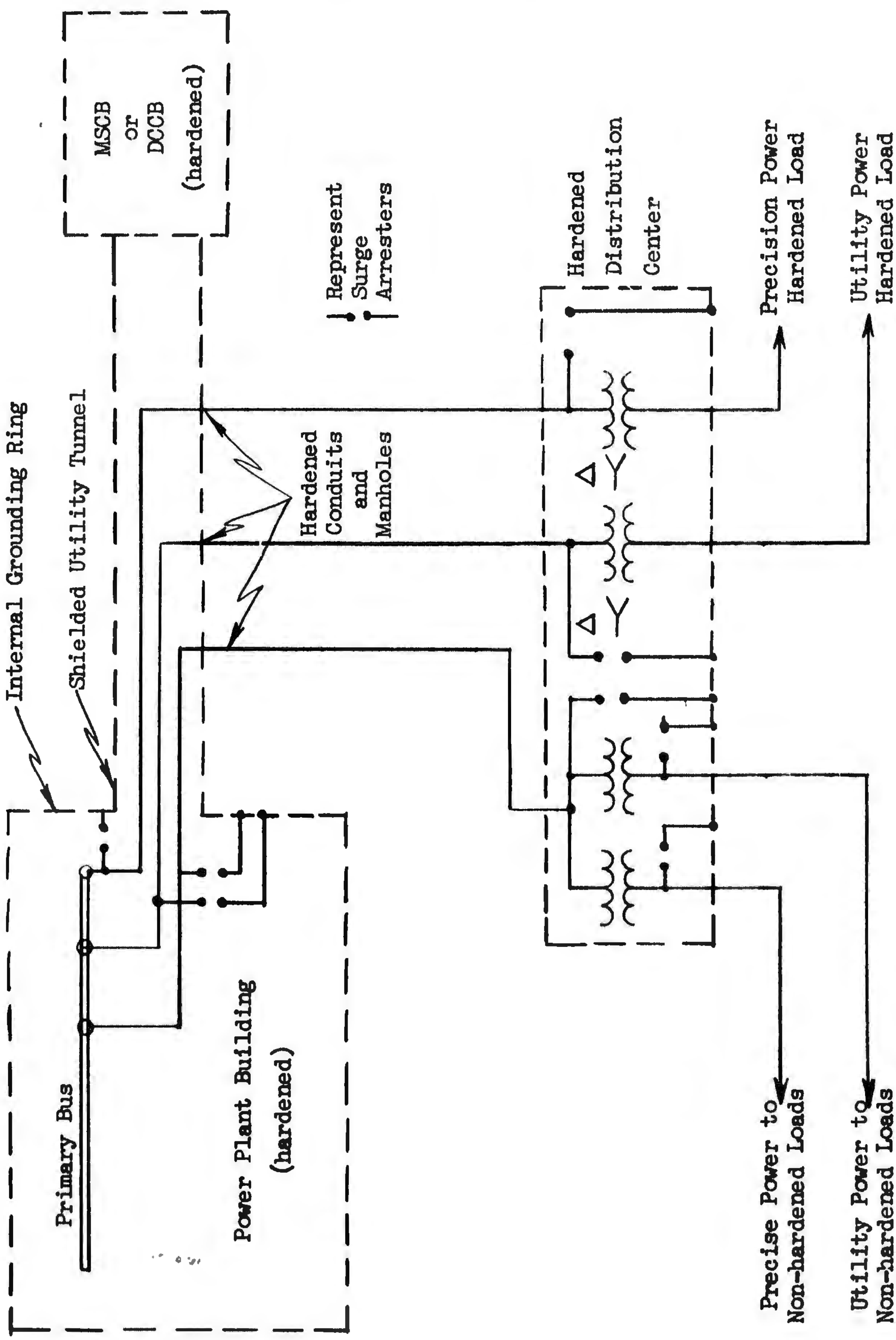


FIGURE 5.56 Surge Arrester Application for Hardened and Non-hardened Loads

that it was well grounded and that under no conditions could the steady state system voltage rise high enough to cause arrester sparkover, arresters rated at 9 kV could be installed. Arresters of this rating would have a ratio E_a/E of 0.65 and would be termed "65% arresters".

Under average conditions, a 9 kV station-class arrester would be expected to hold the line-to-ground voltage to 29 kV or less, which would be about 2.6 times the crest value of normal line-to ground system voltage.

EXAMPLE 2: Class B - Effectively-Grounded System Neutral

If a 13.8 kV system study indicated that the neutrals of the system were effectively grounded and that the limiting reactances and ratios shown in Table 5.5 established it as a Class B system, commercial arresters rated at 12 kV (nominally 80% arresters) would probably be selected.

Under average conditions, a 12 kV station-class arrester would be expected to hold the line-to-ground transient voltage to about 38 kV or less, which would be about 3.4 times the crest value of normal line-to-ground voltage.

For a Class B system, a specially designed arrester rated at about 10 kV (nominally a 70% arrester) might also be considered. A linear interpolation between the protective characteristics of 9 kV and 12 kV station-class arresters would indicate that with such an arrester, the maximum line-to-ground transient voltage would be held to about 32 kV or about 2.8 times the crest value of the normal line-to-ground system voltage.

For either Class A or Class B systems surge voltages could be reduced still further, but this would require a very special arrester with reduced margins and safety factors on the gap sparkover levels and the Varistor valve elements. Since it is unlikely that the equipment would be damaged by surges of this level, it is not believed advantageous to try to limit surge voltages to levels under those provided by commercial arresters.

EXAMPLE 3: Class D - Ungrounded System Neutrals

If, for tactical reasons, the 13.8 kV electrical system is operated with neutrals ungrounded, arresters rated at 15 kV will be required. Such arresters are designated "100% arresters" and station-class units could be expected to hold the line-to-ground transient voltage to about 49 kV or about 4.3 times the crest value of normal line-to-ground system voltage. It is important to understand that on power systems operated with neutrals ungrounded, circumstances may exist which could cause arrester failures.

5.5 Filters

5.5.1 General Aspects of Filter Usage

Filters are combinations of circuit components designed to pass currents and voltages at certain frequencies, but attenuate them at other frequencies. They usually utilize the resonance characteristics of series and parallel combinations of inductance, capacitance, and resistance. Filters reduce interference by introducing a high impedance in series with the interference currents and/or shunting interference currents to ground through a low impedance.

The application and design of filters requires specific and detailed knowledge of the source and load impedances, power transmission requirements and attenuation requirements of the circuit to be filtered. With this data available, any competent filter designer can provide a filter design. For power systems where transient overvoltage limitations are specified for the main supply bus and non-sensitive loads, filter application is limited. The most effective filter location is then between the main supply bus and a transient overvoltage source such as an electric utility system.

Filters in this location are required to pass the total power system load and are necessarily special design problems beyond the scope of these preliminary protective measures. Such filters may be especially designed

cable assemblies (19), tuned circuits connected to tertiary windings of transformers or synchronous motor-generator sets, or may be of the absorptive types. (Application details for synchronous motor-generator sets are given in Section 5.6.)

5.5.2 Specific Applications for Filters

Specialized filters, designed to attenuate extraneous energy coupled into power, control, and communication circuits terminated within shielded areas are commercially available.

5.6 Circuit Isolation by Application of Synchronous Motor-Generator Sets

One method of completely preventing the surges originating in an external power system (utility tie) from transferring into the power system is to interpose a synchronous motor-generator set between the two systems.

Rotating electrical machines have a surge strength lower than distribution lines. It is, therefore, essential that the motor (synchronous machine normally supplied from the external system) be protected by arresters and capacitors from high voltages and steep-front surges originating on the external power system. It is particularly important that this protection be entirely adequate, as otherwise the introduction of the motor-generator set may cause more incidents than would be the case without it.

The high voltage side as well as the low voltage side of the transformer between the external power system and the motor-generator set will already have lightning arrester protection. If this transformer is directly adjacent to the motor, the low voltage side protection, with possible addition of rotating machine capacitors, could apply to both the transformer and the motor. However, in case the transformer is not directly adjacent to the motor, surge protection equipment should be applied both at the transformer and at the motor terminals. In addition, just as in the case of the power plant generators themselves, surge protection shall be applied at the generator.

To assure continuity of service in case of damage either to the synchronous motor or generator, a by-pass/isolation switch shall be installed

with the set. This switch, which would by-pass the motor-generator set and isolate it from the external power system and the power plant generating system, would be operated only when the motor-generator set is taken out of service. It would not seem necessary to have a spare motor-generator set in each installation. However, it would be advisable to have a spare set which could be transported wherever necessary to minimize the time required for maintenance or repair and return to the normal mode of operation with the by-pass open.

The use of a motor-generator set requires that provision be made for starting the motor from the external power system. The simplest method would be the use of full-voltage for starting.

Another application of motor-generator sets that should be considered is to isolate from the external power system and supply only particularly critical loads from the set. It would seem possible by this means to have two levels of performance on the two types of loads. This isolation of critical loads may also be desirable to protect against surges originating within the power plant itself, as distinguished from those originating in the external power system. Again, as in the first case considered, the motor-generator set supplying critical loads should be equipped with a by-pass/isolation switch and fully protected with arresters and capacitors.

In summary, there are four possibilities in connection with motor-generator application:

1. Direct connection to the utility and common supply for all loads with set by-passed.
2. Isolation of the entire power plant system from the utility by synchronous motor-generator set(s).
3. Isolation of particularly critical loads in the system by motor-generator set.
4. A combination of the use of both (1) and (2) above, if this is considered feasible.

5.7 Solid State Power Converters for Circuit Isolation

A second method of completely preventing transient overvoltages which are generated external to a sensitive load or circuit from appearing on the sensitive circuit is to interpose a solid state power converter between the source of disturbance and the sensitive circuit. The principle used in solid state power converters is illustrated in Figure 5.57.

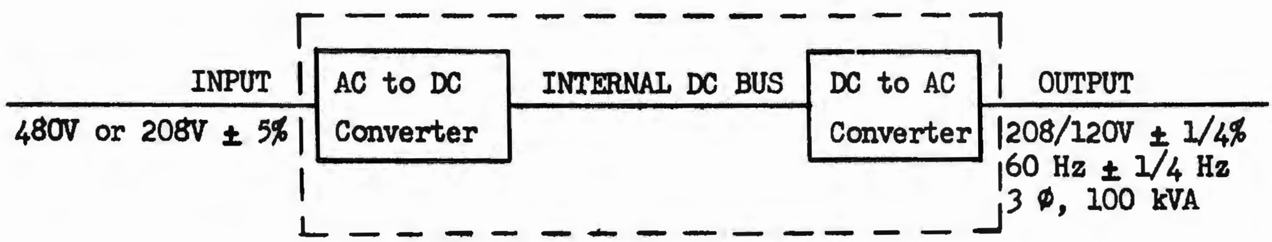


FIGURE 5.57 Solid State Power Converter

As is illustrated in the sketch, the incoming 60 Hz power is isolated from the output by first converting to direct current and then inverting to obtain an alternating current output. The input and output frequencies can be either synchronous or asynchronous. The sketch indicates a load capacity of 100 kVA. Larger loads can be supplied by paralleling units. Converter units having smaller output capacities are, of course, available.

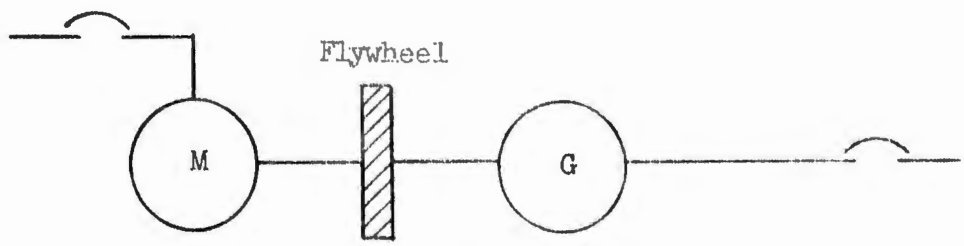
These solid state power converters cost approximately three times as much as motor-generator sets and have a mean time between failure (MTBF) of 20,000 hours.

5.8 Uninterrupted Power

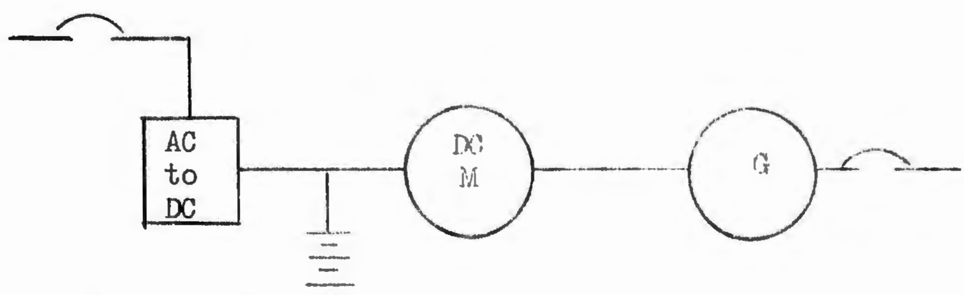
Uninterrupted or "no break" power is often required by critical loads. When specifying requirements for uninterrupted power, particular attention must be given to the time period between the failure of primary power and the assumption of load by the auxiliary or stand-by power. Allowable voltages and frequency magnitude changes and the permitted time duration of

such changes must be clearly stated for this time period.

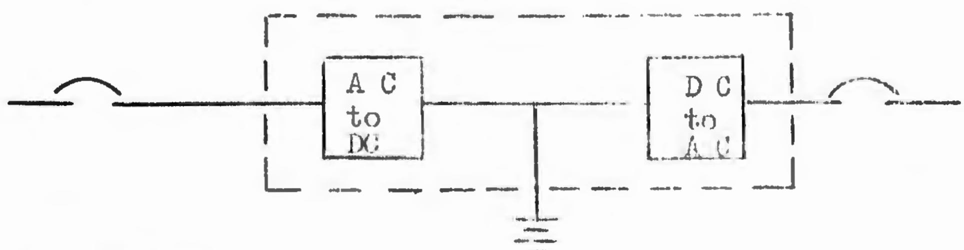
Several concepts for supplying uninterrupted power are presented in Figure 5.58. In (A) of this figure a flywheel is used as the energy storage device. Obviously, this concept is able to supply power for only a few seconds unless the flywheel is extremely large. In (B) a battery is substituted for the flywheel. The next concept, (C), is a solid state version of (B). In (D) an engine has been added to the concept shown in (A). For long time delivery of power from auxiliary sources, an engine driven battery charger can be added to either (B) or (C).



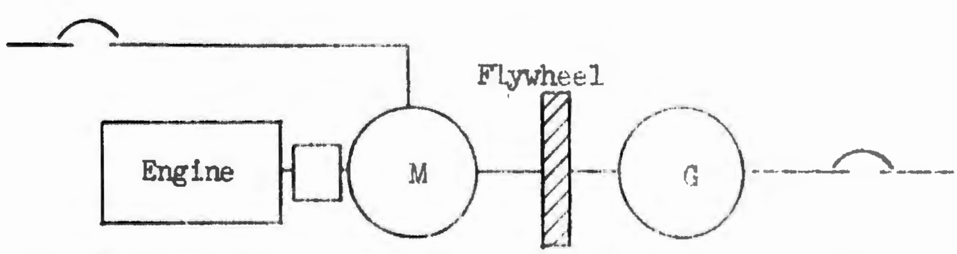
A. M-G Set, Flywheel Energy Storage



B. M-G Set, Battery Energy Storage



C. Solid State Power Converter, Battery Storage



D. M-G Set, Flywheel Short Time Energy Storage, Prime Mover Long Time Storage

FIGURE 5.58 Uninterrupted Power Concepts

6.0 SPECIAL SYSTEMS

This section has been identified to cover the EMP protection problems of special electrical systems and subsystems not presently envisioned.

7.0 ELECTROMAGNETIC PROTECTION COMPATIBILITY

7.1 Introduction

This section introduces the desirability and requirements for evaluating NEMP, radio frequency interference, lightning, and switching surge electrical system protection requirements with the objective of producing a balanced and most effective design. Also to be considered are protection requirements which are directed at things other than the electrical system.

For instance, certain areas of the MSCB and DCCB require considerable RFI type shielding for personnel protection from transmitter electromagnetic energy. NEMP design criteria which may require shielding in these areas must recognize the existence of the personnel shielding criteria so that shielding duplication is minimized. To further illustrate this kind of a comparison, Table 7.1 was prepared to detail those site locations requiring electromagnetic protection. The table identifies these site locations in relation to the need for electromagnetic protection from lightning, NEMP, electric utility transients, power system switching, and transmitter electromagnetic energy at these locations.

7.2 Overvoltage Tolerance

Electric and electronic systems have varying levels of tolerance for transient overvoltage. These tolerances usually cannot be simply stated in magnitude values. The time duration of the overvoltage is equally important. So, for overvoltage tolerances to be useful, the time characteristics, as well as magnitudes, must be known.

Overvoltage tolerances for electronic loads have not been established in the form of industry standards, as has been done for electric utility system apparatus. The electric utility system tolerances are the result of an evolutionary process of achieving an economic balance between manufacturers supplying equipment to operate on systems where transient overvoltages exist and the development of protective equipment and techniques of limiting transient overvoltages. Table 7.2 lists typical system components,

TABLE 7.1

SITE LOCATIONS REQUIRING ELECTROMAGNETIC PROTECTION

Sensitive Location	Energy Source: Lightning	NEMP	Electric Utility Transients	Power System Switching Transients	Transmitter EM Energy
Power Building					
Generation	None Req.	Required	Required	None Req.	None Req.
Distribution	" "	"	"	" "	" "
Control	" "	"	None Req.	" "	" "
Personnel	" "	None Req.	" "	" "	" "
Facilities					
MSL Farm	Required	Required	Note 1	None Req.	None Req.
Adm. Support	"	None Req.	" "	" "	" "
Power	"	Required	" "	" "	" "
Personnel	"	None Req.	None Req.	" "	" "
DCCB					
Electronic	None Req.	Required	Note 1	None Req.	Required
Utility	" "	"	" "	" "	None Req.
Personnel	" "	None Req.	None Req.	" "	Required
MSCB					
Electronic	None Req.	Required	Note 1	None Req.	Required
Utility	" "	"	" "	" "	None Req.
Personnel	" "	None Req.	None Req.	" "	Required

Note 1: Protection against possible effects of electric utility transients must be accomplished in power building and/or as part of the distribution system.

TABLE 7.2

MAXIMUM TRANSIENT VOLTAGE TOLERANCE LEVELS FOR ELECTRICAL EQUIPMENT

Nominal System Voltage L-L (kV)	Transformer (Oil-immersed)		Induction Requirements		Instrument Transformers	Transformer Dry Type	Motors	Generators	Relays and Solenoids
	Under 500 kVA	Over 500 kVA	Under 500 kVA	Over 500 kVA					
	O.V.	O.V.	O.V.	O.V.	O.V.	O.V.	O.V.	O.V.	O.V.
13.8	3.85	3.85	3.85	3.85	3.85	3.45	2.46	2.46	-
4.16	6.05	6.05	6.05	6.05	6.05	6.05	2.88	2.88	-
2.4	6.1	6.1	6.1	6.1	6.1	6.1	3.15	3.15	-
0.48	15.5	15.5	15.5	15.5	15.5	15.5	5.88	5.88	-
0.208/ 0.120	16.2	-	16.2	-	16.2	16.2	10.8	10.8	16.6

O.V. denotes overvoltage. Overvoltages are given in terms of the line-to-ground system voltages.

rated voltages, and power supply peak transient overvoltages which the components can be expected to withstand without damage or malfunction. The transient overvoltage is given as a per unit value of the line-to-ground operating voltage.

A comparison of the per unit overvoltages listed in Table 7.2 with the component NEMP responses given in Section 4.0 shows that the power system components will not be damaged by NEMP and no special NEMP protection is required to prevent component damage or malfunction.

Many electronic type loads which are connected to 120 volt circuits will not tolerate the transient overvoltage magnitudes given in Table 7.2. It becomes desirable, therefore, to design complex systems in a manner which permits the separation of voltage sensitive electronic loads from the much less sensitive power and utility circuits. If this practice is followed, special protective schemes such as filters or motor-generator sets need only be applied to the sensitive circuits.

8.0 QUALITY ASSURANCE

8.1 Introduction and Scope

Quality assurance for protection of the power plant and facilities electrical systems against NEMP effects embraces any function, process, specification, or procedure designed to control electromagnetic pulse energy so that electrical system performance is not impaired and which assures that the NEMP protection requirements are satisfied.

In an NEMP environment satisfactory electrical system performance will be assured if the protection recommendations and techniques detailed in the foregoing sections of this document are integrated into the system design and followed during all stages of project development. Thus, quality assurance involves close coordination of system design features with adequate specifications and proper procedures relating to the procurement, construction, installation, inspection, evaluation/testing, periodic surveillance and maintenance of the shielding, grounding, surge suppression, filtering, and isolation subsystems.

This section is intended to outline important requirements that will assure quality performance of the NEMP protection subsystems. While any quality assurance program cannot be executed until working specifications have been prepared and the system reaches a "hardware" stage, much of the bridging between criteria, design, and actual application can be formulated by advanced planning.

8.2 Quality Assurance Measures Relating to Procurement

8.2.1 Electrical Conduit and Fittings Specifications

1. All electrical conduit and fittings shall be rigid steel or wrought iron unless otherwise specified in the design. Mixed materials shall not be requisitioned.
2. Conduit of standard wall thickness and not less than two-inch electrical trade size shall be ordered for outside use. Conduit of

standard wall thickness and not less than one-inch trade size shall be ordered for inside use.

3. Conduit bends and elbows shall conform to those specified on the drawings. In no case shall bending radii be less than minimum standard. Requisitions for flexible conduit couplings (bellows) or expansion joints should specify dimensions, threads, kind of materials, and the number of shunting braids. If couplings with shunting braids are not available, equivalent conductivity bonding straps and approved connectors shall be ordered.
4. Conduit fittings and conduit sections shall be threaded at both ends and male threads shall be protected from damage during shipping and handling.
5. Condulets should not be procured unless specifically called for on the design drawing and parts list.
6. Conduit requisitions should state that sections shall conform to standard dimensions, within tolerances, for length, diameter, and wall thickness. Sections shorter than standard shall not be ordered unless specified by the designer.
7. Protective bushings for conduit terminations shall be of steel or wrought iron.
8. Pull boxes, splice boxes, junction boxes, manhole and handhole liners ordered for use in the conduit subsystem shall be of steel or wrought iron and shall be constructed of metal having thickness and metallurgical characteristics which meet the design specifications.
9. Orders for coatings, platings and/or inside and outside surface treatments shall conform to the design specifications.
10. Only specifically approved welding materials, fluxes, cleaning solvents, and conductive sealants shall be ordered for conduit and fittings assembly.

11. Spare part requisitions shall include a supply of Erickson couplings for special applications and/or repairs.

8.2.2 Utility Piping and Fittings

1. Requisitions for metal utility piping and fittings shall state that these shall be of good quality, homogeneous material and conform to a design specification that all joints will be electrically continuous.
2. Insulating joints shall not be ordered unless specified on the parts list.
3. There are no procurement restrictions regarding NEMP applying to non-metallic utility piping and fittings.

8.2.3 Counterpoise, Grounding, and Bonding Subsystem Materials

1. Bulk materials such as cable, ground rods, bonding straps, and bar copper should be ordered in strict conformity to specifications governing the kind of metal, dimensions, conductor size, and stranding.
2. The buried counterpoise design shall provide for requisitioning enough cable to allow for slack in the individual cables during installation to minimize breakage resulting from earth settlement or movement.
3. Only approved electrical connectors, brazing materials, and fluxes chosen on the basis of galvanic compatibility shall be ordered for assembly of this subsystem.

8.2.4 Shielding Subsystem Materials

1. Bulk materials intended for building and/or room shielding, such as rebars, metal screening, welded wire fabrics, solid metal plates, etc., shall be requisitioned on the basis of the design specifications considering kind of material, weldability, formability, conductivity, and permeability, ASTM requirements, standard widths, diameters, lengths, mesh sizes, and thicknesses; also

shipping and handling weights. It shall be the designer's prerogative to requisition samples of shielding for investigation and to procure independent testing services to evaluate them or to referee disputed evaluations.

2. Materials and fittings for the fabrication of joints in shielding, for installing the shielding, and for making any kind of attachments to it shall have the designer's approval before orders are placed.

8.2.5 Shielded Rooms

1. Procurement specifications for commercially-built shielded rooms shall include the following information which shall be furnished by the designer:
   a. minimum attenuation required.
   b. frequency or bandwidth of the interference to be excluded.
   c. room dimensions.
   d. kind of material desired, usually selected on the basis of environmental requirements, type of occupancy, frequency of use, etc.
   e. nature, location, and size of doors, penetrations, and utility openings.
   f. placement of equipment within the shielded volume.
   g. any special requirements not covered by the above.
2. Procurement specifications shall include a requirement that commercial NEMP shielding shall be evaluated by measurement of its ability to attenuate low impedance (magnetic) fields at frequencies of 10,000 Hz and higher in accordance with the procedures stated in MIL-STD-285 entitled, "Military Standard Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of", latest revision or superseding document(s).

3. The manufacturer of commercially shielded rooms shall be required to demonstrate satisfactory attenuation characteristics for the rooms with all openings, penetrations, etc. in place. The requirement in Item (2) above may be waived provided the manufacturer's measurement techniques are deemed to be acceptable and the actual performance of the shielding can be shown as equal to or exceeding that measured by following MIL-STD-285.
4. Because of the specialized nature of custom-built shielded rooms, requisitions should stipulate that factory-trained personnel erect and test them and quotations should be obtained on this basis.
5. For shielded rooms and buildings which are not commercially procured the designer shall issue instructions and material lists for all items to be purchased, including techniques for erection and evaluation after all openings and penetrations are in place. In this connection a number of vendors can supply pre-cut shielding panels, shielded modules and joining materials, together with complete plans for assembling shielded rooms of any size. Since qualities, methods of rating the shielding effectiveness, and clarity of instructions may vary over a wide range, it may be desirable in certain cases to request samples of the panels and/or fittings for investigation and evaluation before placing a complete order.

8.2.6 Equipment Enclosures

1. In some NEMP environments being considered, standard equipment enclosures will not provide enough shielding for contained equipment. Procurement of proper enclosures shall, therefore, be in strict conformity to overall design requirements, considering:
   a. function of the enclosure (cabinet, console, or case).
   b. dimensions of the enclosure.
   c. material and configuration, usually selected on the basis of

required shielding effectiveness (dB), structural needs, galvanic compatibility in the environment, etc.

d. feasibility of fabrication, which includes formability and weldability, to obtain the desired configuration.

e. relationships of thermal, electrical, magnetic, and physical properties of the contained equipment and the enclosure. This includes ventilation needs, electrical clearances, accessibility of equipment for replacement or repairs, etc.

f. location and nature of openings for service entrances, meters, relays, and details of construction around such openings.

g. grounding arrangements and requirements.

2. Where required, approved RFI conductive gaskets or sealants shall be procured for the following interfaces:

   a. conduit/enclosure

   b. environmental control/enclosure

   c. panel/flange

   d. any others specified in the enclosure design.

3. To assure the effectiveness of shielding at interfaces in metal enclosures, all mating surfaces must be free from corrosion, paint, or surface contaminants. Wherever possible, procurement specifications shall delineate the specific locations on enclosures which must be free from corrosion and surface contaminants. Requisitions should require suitable protection of these surfaces during shipment and storage so that a minimum of surface cleaning and preparation will be necessary at installation.

8.2.7 Penetrations and Openings in Shielding

1. Requisitions for specialized fittings, plates, and mesh materials needed to insure NEMP protection performance at penetrations and openings shall also conform to design requirements. The gamut includes:

a. Metal plates and mesh materials required in conjunction with conduit and metal utility piping penetrations into unshielded building walls or walls shielded with rebars or welded wire fabric.

b. Welding, brazing, corrosion-proofing materials, and sealants needed in the construction of penetrations.

c. Specialized shielding items such as personnel and equipment access doors, observation windows, vestibules, wave guides, and honeycombs used in openings for conduits, cable trays, utility piping, cooling, heating and ventilating ducts, plenums, or for personnel and equipment access in lieu of doors, as well as portable shields required for protection of openings created by certain maintenance operations.

8.2.8 Surge Protection Devices

1. Procurement of surge protection devices such as wave-sloping capacitors, lightning arresters, overcurrent devices, and low voltage semiconductor type protectors shall be in accordance with the system designer's recommendations governing the application of such devices, based on Sections 5.2.2.3.8 and 5.4.2 of this document. Major design considerations include:

   a. allowable surge magnitudes, steepness, and durations permitted at designated locations on the system.

   b. time/overcurrent or time/overvoltage characteristics of the protected equipment.

   c. comparative performance characteristics of the surge protection device(s).

   d. degree of ground isolation of the system neutral on wye-connected systems.

   e. existence of external utility tie connections.

   f. proximity of protective devices to the equipment to be protected.

g. adequacy of grounding

h. available system fault current at protected points.

i. physical factors dictating electrical clearances, proximity to vulnerable equipment, etc.

j. for low voltage protectors, whether the device is or is not "self-clearing".

2. Requisitions for specified surge protection devices shall include statements that the manufacturer shall successfully demonstrate the device's capability to protect the equipment under test conditions that are mutually acceptable to the manufacturer and the system design engineer. Such acceptance tests shall be performed prior to shipment.

8.2.9 Isolation Equipment and Filters

Procurement instructions relating to quality performance of these items will be issued later.

8.2.10 Procurement of Cathodic Protection Subsystem Equipment

The need for cathodic protection will be dictated by soil corrosiveness at the individual site, expected annual rainfall, height of water table relative to depth of site structures, the extent to which galvanically compatible materials have been selected in the design and how carefully corrosion inhibiting coatings have been applied. These factors are all measureable or predictable, but their interpretation and translation into cathodic protection requirements usually is delegated to corrosion specialists.

1. Requisitions for cathodic protection equipment should, therefore, be prefaced by contracting for the services of a competent corrosion engineer to conduct a survey of the site corrosiveness prior to the start of excavating. This work could be combined with contracts for test borings and other site considerations. Authoritative recommendations can be relayed to the designer as to whether any cathodic protection is necessary and if it is, what is required.

2. Procurement of cathodic protection equipment shall be in accordance with resulting design specifications and may consist of protective metal, concrete, and/or asphaltic coatings applied to certain site structures and equipment, expendable (sacrificial) metal anodes set in backfills of bentonite and gypsum, and/or an electrical (opposing voltage) cathodic protection system requiring rectifiers and special drain beds.
3. Requisitions should also provide for the services of a competent corrosion engineer to properly adjust an electrical cathodic protection system during the initial "polarization" period, and thereafter as required.

8.3 Quality Assurance Measures Relating to Construction

Implementation of the various NEMP protection techniques involves the following construction items:

1. Trenching and excavating done in connection with the conduit subsystem, the counterpoise and grounding subsystem, and cathodic protection drainage beds.
2. Assembly of counterpoise and grounding subsystems.
3. The application of NEMP shielding to buildings and structures.

Quality assurance measures relating to each of these phases of construction are covered in the subsections which follow.

8.3.1 Trenching and Excavating Specifications

1. Trenches for conduit runs shall conform in width and in depth to design specifications and should preferably be pitched so as to eliminate anywhere along a run low "pockets" in which water or other liquid contaminants can accumulate.
2. Trenching for conduit runs between manholes shall be kept as straight as possible; also, abrupt changes in depth shall be avoided. Any rock projections or obstructions that could interfere with subsequent conduit installation shall be removed.

3. To minimize earth settling, trenches should not be cut deeper than required and then partially backfilled to adjust grade, but if this is necessary, the backfill shall be well tamped at the final grade.
4. Prior to excavating for the counterpoise and grounding subsystem, test borings should be made to obtain data on the character of soil at various depths below the surface, soil resistivity and corrosiveness, the presence of underlying rock strata, proximity of water table, etc. Besides dictating the grounding and counterpoise subsystem design, such technical data are useful in other engineering and construction considerations.
5. Excavation work for the counterpoise and grounding subsystem shall conform in location and in depth to design specifications and should be kept on as nearly a level grade as practicable. Rock overlays and other projections or obstructions above base grade shall be removed. In cases where excavation below base grade is necessary to remove obstructions, the backfill to adjust the grade shall be of well-compacted site soil.
6. If soil corrosiveness at the site dictates an electrical cathodic protection system, excavation shall also include the construction of remote drainage beds. These shall be in strict accordance with designs approved by corrosion consultants.

8.3.2 Assembly Specifications for Counterpoise and Grounding Subsystems

Design specifications for the counterpoise and grounding subsystems shall be issued prescribing the locations, interconnections, and construction details of these subsystems and shall include directions to assure quality workmanship during construction. Assembly specifications follow.

1. Only bare, continuous conductor conforming to design specifications shall be used for the assembly of counterpoise grids. Individual grid conductors shall be spaced in a mesh configuration allowing enough slack in the individual cables to preclude breakage from

earth settlement or movement. When the counterpoise system is used in conjunction with driven ground rods, the grid shall extend at least eight feet away from building walls or foundations.

2. Counterpoise grid conductors shall be connected at grid intersections using approved connectors or approved welding and brazing techniques.
3. Risers conforming in dimensions and material to the design requirements shall be connected to the grid conductors using approved methods at points closest to their prescribed final locations. Although #6 AWG copper conductors are considered electrically adequate for this purpose, they should be suitably protected during the construction phase or larger conductors that will withstand the mechanical abuse associated with the construction phase should be specified.
4. Adequate clearances should be provided between building or structure footings and the buried counterpoise grid so that earth settlement will not result in excessive pressure on the grid or its connections. (Some of this effect can probably be minimized by adequate subsoil compaction.)
5. Ground rods of prescribed length(s) shall be driven into the compacted subsoil along the outside perimeter of the grid at the intervals stated in the construction specifications. These rods shall be connected to the counterpoise grid using approved connectors or approved welding and brazing techniques.
6. When subsoil conditions prohibit driving ground rods to the required depth, spacings of the rods shall be reduced and more rods shall be driven to achieve the desired equivalent resistance.
7. Where rock strata preclude any driven ground rods, a larger counterpoise grid shall be assembled in order to attain the minimum ground resistance specified by the designer.

8. Assembly instructions shall include the interconnection of counterpoise and grounding subsystems under the power building, the shielded utility tunnel, and the MSCB or DCCB using approved techniques.

8.3.3 Shielding Construction Specifications

Construction specifications for NEMP shielding of buildings, structures, or equipment rooms shall be based upon the construction practices recommended in Section 5.3.3.2 for solid metal plate shielding, Section 5.3.4.2 for rebar shielding, and Section 5.3.5.2 for welded wire fabric shielding.

Features of the building, structure, or room construction shall provide for openings in the reinforced concrete for personnel and equipment access, as well as for piping, ducting and conduit penetrations, and the like. Such features shall, therefore, be considered in the quality assurance measures applicable to construction rather than installation.

8.3.3.1 Quality Assurance Measures for Application of Solid Metal Plate Shielding

1. Metal plates for shielding shall be inspected before application to determine if they conform to the procurement specifications (Section 8.2.4) and to ascertain that they are in prime physical condition. Bent, dented, corroded, perforated, cut, or off-size plates shall be rejected for use as shields.
2. Plates shall be physically supported on walls, ceiling, and floor in a manner approved by the designer and shall be continuously welded or brazed to form a complete shield, using materials and techniques that have been approved for galvanic and magnetic compatibility. Fillet plates shall be applied to inside shielding if specified on the drawing.
3. Openings in the shielding for personnel and/or equipment access and for piping, ducting, conduit penetrations and the like shall be constructed in strict conformity to the design specifications.

If of metal, piping, ducting, or conduit shall be continuously welded to the shielding at all points of penetration.

4. An overall inspection shall be made of the shield after all construction is complete to determine whether any minor repairs or adjustments are necessary before testing.

8.3.3.2 Quality Assurance Measures for Application of Rebar or Welded Wire Fabric Shielding

1. Rebars and welded wire fabric shall be inspected before being used in the building construction to determine if they conform to the procurement specifications (Section 8.2.4) governing their suitability if used as shields. Materials that are damaged, have loose or fractured welds, welding burns, or are undersized shall be considered as unsatisfactory for shielding applications.

2. Inspections shall be conducted in the course of construction to insure that rebars and welded wire fabric are welded to form continuous loops enclosing the structure, building, or room. For rebars the length of welds shall be at least three times the diameter of the rods and for welded wire fabric the length of welds shall be at least five times the diameter of the wire. All rebars and all wire strands shall be joined. In either construction, the weld cross section shall be sufficient to prevent breaking during construction and handling. Only welding materials and techniques that have been approved by the designer shall be used in the assembly of this shielding.

3. Openings into shielded areas for personnel and/or equipment access and for piping, ducting, conduit penetrations and the like shall be constructed in strict conformity to design specifications. Inspections shall be made before placement of concrete to confirm that:

   a. All rebars or welded wire fabric strands are adequately welded to metal strips or suitable structural sections encasing

openings (Figures 5.36 and 5.48).

b. If required, wave guides of proper dimensions are continuously welded to such strips or sections.

c. At conduit or metal utility piping penetrations, approved solid metal plates having an area at least ten times the area of the penetrations are welded around their perimeters to the rebars or welded wire fabric (Figure 5.14).

d. Metal sleeves through the wall are continuously welded to these penetration plates.

4. No concrete shall be placed until a final inspection indicates that all the approved practices relating to the construction of shielding, penetrations, and openings have been properly executed or corrected.

8.4 Quality Assurance Measures Relating to Installation/ Inspection of NEMP Protective Equipment

Sections 8.4.1 and 8.4.2 outline supervisory and inspection procedures that shall apply during the installation of the electrical conduit and wiring subsystem and metal utility piping in order to insure shielding integrity and freedom from adverse NEMP effects.

8.4.1 Specifications for Installation of Electrical Conduit and Fittings, and Metal Utility Piping and Fittings, including Shielding Penetrations

The installation work covered by this section consists of assembling conduit runs or metal utility piping and making proper bonds and interconnections of conduits and piping to the counterpoise and grounding system at strategic locations along runs and at shielding penetrations.

Design requirements for electrical conduits and utility piping may dictate their installation in insulated ducts or in tunnels to facilitate access for installation, inspection, and maintenance. Alternatively, however, the specifications for such conduits and piping may require installation directly in trenches; in this case, corrosion-resistant coverings will

probably be necessary.

To insure proper installation and quality performance of the electrical conduit subsystem, recommended procedures are as follows:

1. Inspect conduit ducts, tunnels, or trenches before the installation of conduit to ascertain that they are free of obstructions or sharp bends. Abrupt changes in direction and/or grade usually will dictate the installation of manholes or vaults.
2. Install only conduit and fittings that have passed pre-installation inspections, which shall include the following:
   a. Confirm that rigid steel or wrought iron conduit and fittings have been furnished. Steel plumbing pipe shall not be used in place of rigid conduit. Electrical metallic tubing (EMT) or aluminum conduits and fittings are permitted only at locations specified by the designer. Such conduits should be identified by distinguishing marks, colors, or numbers to fit the particular assembly on which they will be used.
   b. Ascertain that the conduit and fittings conform in construction and dimensions to those specified for the particular application. This is especially important for flexible tubing (bellows) fittings.
   c. Check the outside and inside surface coatings on the conduit and fittings to be sure that they agree with the specifications.
   d. Inspect the conduit and fittings for evidences of physical defects or damage. Reject material having any of the following defects:
      - Bowed lengths of conduit
      - Deformed, split, or dented conduit or fittings
      - Shorter than standard lengths of conduit
      - Conduits without a threaded coupling on one end and a suitable thread protector on the other end.

- Conduits or fittings with imperfectly cut (chipped, excessively long, or excessively short) or damaged threads. A thread gauge should be used to inspect the mating ends of all conduit and fittings.
- Unreamed conduits or fittings.
- Conduits or fittings with internal constrictions caused by the entrance of foreign material.
- Conduits or fittings with damaged surface coatings (either inside or outside).
- Conduits or fittings with any holes, cracks, cuts, or other visible surface discontinuities.

e. Confirm that conduit bends (factory formed bends) and not condulets have been furnished. Condulets are permitted only at specific locations as ordered by the designer and should be identified by marks, colors, or numbers to fit the particular assembly on which they may be used.

f. Check that all factory-formed conduit bends are radiused in accordance with National Electrical Code requirements for the particular size of conduit specified.

3. Use the following techniques and precautions when assembling conduits and fittings.

   a. Remove the thread protectors or couplings on male threads and inspect threads on both ends of conduit sections or fittings. Do not assemble parts with poorly cut, damaged, or running threads. Ascertain that the conduit or elbow has been reamed and check that no burrs appear on the inside wall.

   b. Clean threads thoroughly to remove all traces of thread-cutting oil, metal chips, and foreign material. Allow solvent to air dry.

   c. If assembled joint is not to be welded, apply approved conductive

sealant to male threads only, making sure that entire threaded area is covered.

d. Immediately assemble joint and torque tightly, allowing excess sealant to exude from joint. Do not wipe because presence of exuded sealant will be evidence on inspection that joint sealant has been applied.

e. For welded joint construction perform steps (a) and (b) above to properly prepare the joint for assembly.

f. Assemble clean joint without conductive sealant and torque tightly.

g. Run a continuous weld around the outside of the joint using approved welding materials. The welding method used and the integrity of the workmanship should be such that the joint is watertight after welding.

h. All conduit joints shall be individually inspected. On welded joints a random sample of the welds, approximately 5%, should be inspected for cracks, fissures, or other defects by means of a magnetic particle type technique (Magnaflux or equivalent).

i. If required on the design specifications, approved fireproofing or corrosion inhibiting coatings shall be applied only after all conduit joints have passed inspection. Follow the application procedures recommended by the coating manufacturer. Some suggested measures to insure adequate coatings are as follows:
   - Ascertain that the coating is applied with reasonable uniformity to the thicknesses specified.
   - Coatings should be applied under good environmental conditions (temperature, humidity, and cleanliness). This will insure proper bonding of impregnants and fillers or setting of concrete. Also, moisture or other foreign materials that could interfere with the quality of the coating should be excluded.

- Coatings should be allowed to thoroughly set before further handling. A final visual inspection and tests with a "holiday detector" should be made before backfilling.
- The backfilling operation should be performed carefully to avoid abrading or damaging the coating.

4. Make field bends in conduit only with proper bending equipment. This will insure against out-of-roundness. Bending radii, measured along the centerline of the conduit, should be at least as great as factory-formed bends. Maximum field bending radii should be specified by the designer.
5. Where required, install flexible joints (bellows) conforming strictly to design specifications formulated from Section 5.3.2.2. Only flexible joints that have passed pre-installation inspections outlined in (2) above shall be used. Threaded connections shall be made as stated in (3) above and care shall be exercised during assembly not to apply any torsional forces to the bellows section. In addition, flexible joints supplied without metallic braids shall be shunted externally by three approved bonding straps having a conductivity equivalent to three #1/0 AWG copper brazed to the conduits adjacent to the couplings.
6. Installation/inspection procedures for rigid or flexible conduit penetrations of outside walls of unshielded buildings or walls reinforced and/or shielded by rebars or welded wire fabric, conforming to design specifications based on Section 5.3.2.2, Figures 5.10, 5.11, 5.12, 5.13, and/or 5.14 are as follows:
   a. For penetrations at or near the counterpoise level, Figure 5.10, determine that the dimensions and the materials of the grounding plate and the grounding strip, as well as the ground strip span, are in accordance with design specifications.
   b. Inspect for continuity, integrity or workmanship, and use of

approved materials and techniques all welds or brazes between the following:

- Conduits and grounding plate.
- Grounding plate and grounding strip.
- Grounding strip and counterpoise cable interfaces.
- Rebars or welded wire fabric, if used as shielding, and counterpoise cables.
- Jumpers across unbraided bellows, if used.

c. After successfully completing steps (a) and (b) above, coat the following elements using methods and materials approved by the designer:

- Conduits and associated welds.
- Grounding plate and associated welds or brazes.
- Grounding strip and associated welds or brazes.
- Flexible joints, if used.
- Shielding bonds, if used.

d. For penetrations above counterpoise level, Figure 5.11, 5.12, and 5.13, determine that the dimensions, spacing, and materials of the grounding plates, the grounding strip, and the metal mesh screening (if required), as well as the ground strip span and the mesh configurations are in accordance with design specifications.

e. Inspect for continuity, integrity of workmanship, and use of approved materials and techniques all welds or brazes between:

- Conduits and grounding plates.
- Connector plate between grounding plates and grounding strip.
- Grounding strip and counterpoise cables.
- Inner grounding plate and metal screening.
- Intersecting metal screening strips.
- Rebars or welded wire fabric, if used as shielding, and

counterpoise cables.

- Jumpers across unbraided bellows, if used.

f. After successfully completing steps (d) and (e) above, coat the following using methods and materials approved by the designer:
   - Conduits and associated welds.
   - Grounding plates and associated welds.
   - Grounding strip and counterpoise cable interface brazes or welds.
   - Metal mesh screening, if used.
   - Flexible joints, if used.
   - Shielding bonds, if used.

g. If telescoping-type penetrations are used, determine that the lengths of telescoping conduit agree with or exceed design specifications and that at least two #1/0 AWG copper bonding straps are securely welded to each telescoping section.

h. If the conduit penetration is through earth, all metal parts shall be coated using approved materials and methods and a leakproof sealing bushing shall be installed.

7. Installation/inspection procedures for rigid or flexible conduit penetrations of outside walls shielded by rebars or welded wire fabric, conforming to design specifications developed from Figure 5.14 are as follows:

   a. For penetrations at or near the counterpoise level follow the procedures outlined in Steps 6a., 6b., and 6c. above and for penetrations above the counterpoise level use the procedures outlined in Steps 6d., 6e., and 6f. If metal entrance sleeves have been provided in the rebar or welded wire fabric shielding during the construction phase (see Section 8.3.3.2, Step 3d.), inspection should be made to check that each penetrating conduit is bonded to the sleeve by at least two #1/0 AWG copper

bonding straps securely welded to the entering conduit. For telescoping penetrations as shown in Figure 5.15, the inspection should also confirm that the lengths of the telescoping conduit sections agree with or exceed the design specifications.

8. Installation/inspection procedures for rigid conduit penetrations of inside walls shielded by rebars or welded wire fabric, conforming to design specifications evolved from Figure 5.16, are as follows:
   a. Determine that each conduit entering a shielded area is adequately bonded to the internal ground ring on the unshielded side of the wall. The bonding connection should be kept as short and direct as possible and shall have a conductivity of at least #6 AWG copper.
   b. In cases where a group of conduits enter a shielded area, individual conduits shall be continuously welded to an approved metal plate bonded, in turn, to the internal ground ring on the unshielded side.
   c. Inspect for continuity, integrity of workmanship, and use of approved materials and techniques all welds and bonding connections.
9. Installation/inspection procedures for conduit penetrations of inside or outside walls completely shielded by solid sheet steel, conforming to design specifications based in Figures 5.15 and 5.16 are as follows:
   a. Conduits shall be continuously welded to the shielding around the penetration.
   b. Inspect for continuity, integrity of workmanship, and use of approved welding materials and techniques.
   c. On outside conduit penetrations of outside plate shields,

apply an approved corrosion-proofing coating over the inspected welding. Such coatings should completely bridge the coatings on the conduit and the shield.

10. The following installation/inspection procedures apply to the interfaces between the conduit subsystem and manholes, handholes, junction or pull boxes, and equipment enclosures.
    a. Determine by inspection that continuous welds made in conformity to welding specifications exist at interfaces between conduits and the metal liners of manholes and handholes. If welds are satisfactory, apply an approved corrosion-proof coating over the inspected welding. Such coatings shall completely bridge the coatings on the conduit and the liner.
    b. At conduit splice boxes check that all joints have been made in strict conformity to design specifications.
    c. At indoor junction or pull boxes and at equipment enclosures, interfaces with the conduit subsystem shall be inspected to determine that terminations have been made in a manner approved by the designer. Recommended installation methods include the following:
        - Use of double locknuts, one on either side of boxes or enclosure panels. A metal bushing should be used to cover exposed threads.
        - Use of nipple fittings and plates welded to the boxes.
        - Use of retained conductive gaskets on either side of conduit/panel interfaces. These may be indicated in cases where high levels of attenuation are desired and shall be installed in accordance with design specifications.
        - Low interface contact resistance shall be secured by carefully cleaning all mating surfaces. All assemblies shall be inspected for mechanical t ghtness; welds shall be inspected for continuity, integri y of workmanship, and the use of

approved materials and techniques.

11. Since metal utility piping is also required to be electrically continuous, as prescribed in Section 5.3.2.1, the designer shall issue specifications giving approved techniques for making pipe joints and exact installation/inspection procedures suitable for utility piping and fittings. As a guide in the development of these procedures, the conduit penetration recommendations outlined in Steps 6 through 9 above are equally applicable to metal utility piping.

    In those instances where non-metal piping or insulating joints are required to satisfy other design requirements, the non-metal section(s) or joint(s) shall be bonded. Applicable procedures for installing and inspecting bonds are included in Section 8.4.7.

8.4.2 Installation/Inspection Specifications for Electrical Wiring

In this section the term "electrical wiring" connotes wires, cables, and/or buses connecting various elements of the power, control, communications, instrumentation, alarm, and monitoring subsystems.

The basic quality assurance requirement governing the installation and inspection of electrical wiring is that unless routed entirely within an overall shield providing the requisite amount of attenuation from NEMP effects, all wiring shall be contained within rigid steel or wrought iron conduit or specifically approved electrical raceways. In some cases adequately armored and/or shielded cables may be specified, either in lieu of or in combination with conduit containment.

The following recommended installation/inspection procedures are based on Sections 2.0 and 3.0 of this document and are premised upon overall shielding in the control room of the power building and in certain specified areas of the MSCB or DCCB.

1. Install all 13,800 volt or 4160 volt buswork in the power building, the MSCB or DCCB, or other facilities in approved metal bus enclosures. Inspections shall be made at assembly to insure that:

a. All mechanical and electrical connections are made as indicated on the assembly drawings and proper clearances have been maintained.

b. Torqueing specifications are followed.

c. Integrity of workmanship is such that there are no openings or discontinuities.

d. All bends, penetrations, and terminations are made in conformity with the design specifications.

2. If unshielded 13,800 volt or 4160 volt wiring is specified for use in unshielded areas of the power building, the MSCB, or the DCCB, it shall be installed in rigid steel or wrought iron conduit of no less than one-inch electrical trade size. An insulated discontinuity detection wire shall be run through each conduit along with the power wiring. Inspections shall be made to ascertain that the wiring, conduit size, and routing conform to design specifications.

3. If shielded, armored 13,800 volt or 4160 volt cable is specified for use in unshielded areas of the power building, the MSCB or DCCB, it need not be installed in conduits but may be run in cable trays. Inspections shall be made to determine that the cable shields and armor are electrically continuous with terminal equipment enclosures and that the installed wiring and routing conform to design specifications.

4. The designer shall select the insulated shielded lead to be used between generator neutral and grounding device. This lead may be installed in the metal enclosure shielding generator power leads or in a separate conduit. Inspections shall be made to confirm that wiring and routing conform to specifications.

5. Wiring and connections to surge sloping capacitors in each generator housing shall be installed as indicated on the assembly drawings and inspections shall be made to confirm that insulation, connections,

lead lengths, and clearances conform to the specifications. A separate shielded enclosure for the capacitors may alternatively be specified. In this case all connecting leads should be kept as short as possible.

6. Install in approved metal bus enclosures all 480 volt or 208/120 volt buswork in unshielded areas of the power building, the MSCB or the DCCB, or other facilities. Inspections shall be made to insure that:
   a. All mechanical and electrical connections are made as indicated on the assembly drawings and proper clearances are maintained.
   b. Torqueing specifications are followed.
   c. Integrity of workmanship is such that there are no openings or discontinuities.
   d. All bends, penetrations, and terminations conform to design specifications.
7. In unshielded areas within the power building, MSCB or DCCB, all 480 volt or 208/120 volt power wiring shall ordinarily be installed in rigid steel or wrought iron conduit no smaller than one-inch electrical trade size. At the designer's discretion under certain environmental conditions, this requirement may be waived and containment is permissible in rigid aluminum conduit or electrical metallic tubing (EMT). In these special cases condulets may be specified in place of standard elbows. An insulated discontinuity detection wire shall be run through each conduit along with the power wiring. Inspections shall be made to check conformity of wiring, raceway size, and routing with design specifications.
8. All power cables from the power building, the MSCB or DCCB to hardened or non-hardened facilities loads shall be specified as twisted, armored 3- or 4-conductor cables with individual shields

on each phase conductor or three single, armored, shielded cables. Install such cables in rigid steel or wrought iron conduit no smaller than two-inch electrical trade size. An insulated discontinuity detection wire shall be run through each conduit along with the power wiring. Inspections shall be conducted to check that the cable construction, conduit size, and routing conform to design specifications.

9. In the shielded utility tunnel, power wiring installations for the various voltage services may alternatively consist of:
   a. Armored cables with individually shielded phase conductors.
   b. Approved metal bus enclosures.
   c. Unarmored cables contained in rigid steel or wrought iron conduit no smaller than one-inch electrical trade size.

   In the event that bus enclosures are specified, inspections shall be made to insure that:
   a. All mechanical and electrical connections are made as indicated on assembly drawings and proper clearances are maintained.
   b. Torqueing specifications are followed.
   c. Integrity of workmanship is such that there are no openings or discontinuities.
   d. Terminations conform to design specifications.

   If the wiring is specified for installation in conduit, an insulated discontinuity detection wire shall be run through each conduit along with the power wiring. Inspections shall be made to check conformity of the wiring, conduit size, and routing with design specifications.

10. In unshielded areas within the power building, the MSCB or DCCB, control wiring and communications wiring shall be installed in separate rigid steel or wrought iron conduit no smaller than one-inch electrical trade size. An insulated discontinuity detection

wire shall be run through each conduit along with the control or communications wiring. Inspections shall be made to confirm that control, communications, and power wiring are each contained in separated conduits and that wiring, conduit sizes, and routing agree with the design specifications.

11. Control and communications wiring between the power building, the MSCB or DCCB and hardened or non-hardened facilities shall be specified as shielded cables selected by the designer. Such cables shall be installed in rigid steel or wrought iron conduit no smaller than two-inch electrical trade size. At the designer's discretion both control wiring and communications wiring may be routed through the same conduit. An insulated discontinuity detection wire shall be run through the conduit along with such wiring. Inspections shall be conducted to check that such wiring is separated from power wiring and that the wiring, conduit size, and routing conform with design specifications.

12. In the shielded utility tunnel, control and communications wiring may be specified as shielded or unshielded and shall be installed in rigid steel or wrought iron conduit no smaller than one-inch electrical trade size. Inspections shall be made to determine that such wiring is separated from raceways containing power wiring and that the wiring, conduit sizes, and routing are as specified.

13. In unshielded areas within the power building, the MSCB or DCCB, alarm and monitoring subsystems wiring installations shall be made in strict conformity to design specifications. Alarm systems shall preferably employ individual sensing elements. Long open wire sensors such as used on certain heat detectors shall not be specified in these areas. Alarm/monitoring wiring shall be installed in rigid steel or wrought iron conduit no smaller than one-inch electrical trade size. An insulated discontinuity

detection wire shall be run through each conduit along with the alarm and monitoring wiring. Inspections should confirm that the wiring is suitable and that conduit sizes and routing conform to specifications.

14. Alarm and monitoring subsystems wiring between the power building, the MSCB or DCCB and hardened or non-hardened facilities should preferably be designed so that systems at each building or area are wired independently. The wiring between buildings and to a central monitoring location shall be solely for indication signals and such signal circuits shall be electrically isolated from the primary alarm subsystems by relays or transformers. Alarm subsystems should preferably employ individual sensing elements; long open wire sensors should not be specified. Alarm/monitoring wiring shall be installed in rigid steel or wrought iron conduit no smaller than two-inch electrical trade size. An insulated discontinuity detection wire shall be run through each conduit along with the alarm and monitoring wiring. Inspections shall be conducted to check that the installed wiring, the general subsystem arrangement, conduit sizes, and routing conform to design specifications.
15. Within the shielded utility tunnel, installation/inspection procedures for alarm and monitoring subsystems wiring shall be as outlined in Item 14 above, except that the minimum conduit diameter shall be no smaller than one-inch electrical trade size.

8.4.3 Installation/Inspection Requirements for Shielded Rooms and Shielded Equipment Enclosures

8.4.3.1 Quality Assurance Measures for Installation/ Inspection of Shielded Rooms

In this section a "shielded room" is defined as a shielded volume, generally containing openings for personnel and equipment access as well as utility penetrations, where large air spaces are usually present around and

above equipment contained therein. Volumes may range from small room size to entire buildings. Shielded rooms should not be confused with shielded equipment enclosures covered in Section 8.4.3.2.

To assure quality performance of shielded rooms, recommended installation/inspection procedures are as follows:

1. If overall design considerations dictate a shielded control room in the power building, the shielding shall consist of solid metal sheets assembled on site to form a complete envelope with continuously welded seams. Assembly drawings approved by the designer shall specify dimensions and methods of supporting and attaching shielding to the building. Inspection requirements and procedures applying to a basic shielded control room of this design are essentially the same as those outlined in Section 8.3.3.1.

   Openings in the room, such as access doors, observation windows, heating/cooling ducts, and/or wave guides, shall be installed and inspected in accordance with design specifications. Conduit and metal utility piping penetrations shall be installed and inspected in strict conformity to the procedures outlined in Section 8.4.1, Item 9.

2. For shielded rooms assembled on site in other areas such as in the MSCB or DCCB, installation shall be in strict conformity to design specifications. Inspection procedures would depend upon the method of application of shielding. However, with minor modifications, the procedures outlined in Sections 8.3.3.1 or 8.3.3.2 are applicable to a basic shielded room.

   Openings in the room, such as access doors, observation windows, heating/cooling ducts, and/or wave guides, shall be installed and inspected in accordance with design specifications. Conduit and metal utility piping penetrations shall be installed and inspected in strict conformity to the procedures outlined in Section 8.4.1.

3. Where required, commercially-produced shielded rooms or prefabricated

shielding panels meeting the procurement specifications outlined in Section 8.2.5 shall be installed. The project designer shall decide whether such rooms are to be custom-built or assembled from prefabricated panels.

For custom-built installations it is recommended that factory trained personnel erect, inspect, and evaluate the room. For standard installations, instructions furnished by the manufacturer shall be followed during on-site assembly. Inspections shall be made during and after assembly to insure that all shielding elements are fitted properly and that all joints are adequately sealed.

Openings in the room, such as access doors, observation windows, heating/cooling ducts, and/or wave guides, shall be installed and inspected in accordance with instructions prepared by the designer or shielded room manufacturer. Conduit and utility piping penetrations through solid metal plates assembled with the shielding shall be installed and inspected in strict conformity to the procedures outlined in Section 8.4.1, Item 9.

Final evaluation of the shielding room attenuation shall be made after all openings and penetrations are in place. To expedite evaluation the designer or shielded room manufacturer shall issue detailed specifications for making attenuation checks.

Suggested testing procedures are outlined in Section 8.5.

8.4.3.2 Quality Assurance Measures for Installation/ Inspection of Shielded Equipment Enclosures

In this section the term "shielded equipment enclosure" connotes any box, hood, housing, cabinet, case, cladding, console, covering, container, containment vessel or tank, and the like which wholly or partly surrounds an electrical or electronic item or group of items. An enclosure may perform any or all of the following functions:

1. provide physical protection for equipment.

2. provide physical protection from items in enclosure to personnel or objects outside.
3. provide means for installation of ventilating items.
4. provide means for installation of cooling items within enclosure.
5. provide means of enclosed equipment support by external facilities.
6. provide interior support for subassemblies, components, and similar items.
7. provide reduction of radiated audible noise or radiated electromagnetic interference.
8. provide shielding for enclosed equipment from external NEMP fields.

From an NEMP standpoint the shielding function is the one of primary concern, but it should be recognized that a number of the other functions have to be considered in the design of a practical enclosure. Thus, the amount of attenuation provided by a shielded enclosure is largely a matter of design accomplished by coordinating such factors as shielding materials, dimensions, openings, etc. with relevant functions listed above.

The intent of the following installation/inspection procedures is to assure that the level of shielding attenuation provided by the design is achieved in practice.

1. If the shielded enclosure is an integral part of the equipment, which usually is the case for motors, generators, transformers, regulators, and other types of inductive apparatus, installation shall be made in accordance with the assembly drawings. Where attached compartments, terminal boxes, etc. are provided for making up connections, inspections shall be made to check that all leads are completely contained within such compartments, that all interfaces with conduit or other approved electrical raceways have

been carefully made to insure shielding continuity, and that the equipment housing is grounded properly by connection to the nearest internal grounding ring.

2. Shielded equipment enclosures which are not integral with the protected equipment shall be carefully identified prior to installation to insure that the enclosure furnished is the one intended to be used. Many of such enclosures may be engineered to provide specific levels of shielding attenuation and, while resembling each other, may not be interchangeable. Careful coordination of parts lists and assembly instructions will, therefore, be required at installation. Inspections shall be made to insure that:
   a. all contacting surfaces are clean at the time of assembly.
   b. where required, approved conductive gaskets or sealants are applied properly at joints or interfaces between conduits and enclosures, panels and flanges, or other places specified on assembly drawings.
   c. adequate electrical clearances are maintained between energized equipment and the shielded enclosure.
   d. if bolting is used, torqueing specifications are followed.
   e. if welding or brazing is necessary, approved welding or brazing materials and techniques are used.
   f. integrity of workmanship is such that there are no shielding discontinuities and no openings other than those intended.
   g. the equipment enclosure is grounded properly by connection to the nearest internal grounding ring.
3. To maintain shielding continuity and to provide supplementary shielding if required, shielded enclosures for several separated or adjacent equipments may have to be combined. Situations of this kind arise with:
   a. connection of the 13,800 volt or 4160 volt secondary buses

from the utility intertie transformers to the main buses in the power building.

b. connection of main generators to their associated switchgear.

c. connection of main buses in the power building with associated switchgear.

d. containment of exposed connections to liquid-filled transformers, regulators, etc.

e. equipments in housings which provide insufficient shielding to meet the design requirements.

In all these cases, installation and inspection shall be in strict conformity to design specifications. In general, the procedures outlined in Item 2 above are applicable.

8.4.4 Installation/Inspection Requirements for Surge Protective Devices and Lightning Protection of Buildings and Structures

8.4.4.1 Quality Assurance Measures for Installation/ Inspection of Surge Protective Devices

This section covers procedures for the installation and inspection of overvoltage protective devices. Depending upon equipment/component susceptibility and exposure, etc., such devices may be applied to subsystems of all voltage classes and include lightning arresters, wave-sloping capacitors, protective gaps, semiconductor protectors, and the like. The essential installation requirement that all these devices have in common is that they be shunted across equipment to be protected in order to limit the magnitude and/or the rate of change of transient voltages impressed upon equipment as a result of lightning, switching surges, NEMP, etc.

Quality assurance measures associated with these procedures are as follows:

1. Install only approved protective devices that meet the procurement requirements outlined in Section 8.2.8.
2. Inspect the device as received to insure that it is in good physical condition and free from such defects as damaged line and

ground leads or terminals, broken or nicked wire strands, cracked or chipped housings, looseness of assembled parts, defective moisture and/or hermetic seals, etc.

3. Install protective devices in strict accordance with locations, voltage and interrupting ratings, clearances or proximity to protected equipment, method of connecting, type of shielded enclosure, and other application factors specified by the designer. Specific locations at which surge protective devices are mandatory, based on Sections 2.0 and 3.0, are as follows:
   a. A surge sloping capacitor rated at 0.25 microfarad is required between each phase terminal and equipment ground at each power system generator. (Sections 2.4.1, 2.4.2, 2.4.3, item 11, and 5.2.2.3.8)
   b. If the power system has an electric utility interconnection, station type lightning arresters are required between each phase terminal (HV and LV) and ground at each intertie transformer. Surge protection may also be necessary at the incoming intertie cables if they are extensions of an overhead system. (Section 3.6.1, item 5)
   c. Station type lightning arresters are required between each phase of the main power buses and ground in the power building and between each phase terminal (HV and LV) and ground at each transformer feeding non-hardened loads. Arresters are also required between each HV phase terminal and ground at transformers feeding hardened loads, but none are required at the LV terminals to such loads (Section 5.4.2.1).
4. After installing protective devices, check that all connections are properly made before energizing. Bilateral devices are generally not critical to polarity or phase, but unilateral devices may not protect the equipment with line and ground connections interchanged.

8.4.4.2 Quality Assurance Measures for Installation/Inspection of Lightning Protection Equipment at Buildings and Structures

Direct as well as induced lightning strokes often produce severe transient voltages akin to NEMP effects, which can disrupt electrical and electronic equipment in unshielded buildings and structures. While the design of buildings and structures is primarily dictated by their functional requirements, lightning protection is normally an important consideration. Therefore, this section outlines procedures that should be followed in connection with the installation and inspection of lightning protection equipment at the power plant and facilities buildings and structures.

Procedures based on the techniques prescribed in Sections 5.2.2.1, 5.2.2.2, 5.2.3.1.1, and 5.2.3.1.2 are as follows:

1. For metal clad or metal roofed construction, install bonds to insure that all panels, plates, or other sections of metal sheathing materials are electrically continuous. Where roof and side walls of a building or structure are metal clad but not electrically interconnected, they shall be made electrically continuous by installing bonds between the roof and wall sections. Also, if sections of metal are used as gravel stops in metal roof construction, these shall be bonded to the roof.
2. After bonding as outlined above, install the following grounding connections:
   a. from edges of metal roof (if non-metallic sidewalls) to the external grounding system.
   b. from lower edges of metal wall sheathing (if specified) to the external grounding system.
3. Inspect all bonding and grounding connections to insure that they are made properly, checking for
   a. adequate size of bonding and grounding conductors. (Section 5.2.3.1.1)

b. proper materials used for bonding and grounding conductors. (Section 5.2.3.1.1)

c. quality workmanship exercised in welding or brazing and protecting connections from physical and electrolytic damage. (Section 5.2.2.3.2)

4. To protect buildings with non-metal roofing, such as steel-reinforced, concrete structures where the rebars are not looped to afford shielding, install lighting masts or lightning air terminals in accordance with design specifications. As a guide to checking on the proper proportioning of these lightning diverters for the particular structure to be protected, the techniques and references described in Section 5.2.3.1.2 should be followed.

5. Diverter grounds should be inspected to determine that they conform to specifications in dimensions, materials, and configuration and that they are correctly installed with direct connections to the counterpoise or grounding system. The same procedures as outlined in (3) above will apply. Cable sizes and recommended configurations are described in Section 5.2.3.1.2.

8.4.5 Installation/Inspection of Isolation Devices and Filters

Instructions for these items will be issued later.

8.4.6 Installation/Inspection of Bonding and Grounding Connections

This section gives general, as well as specific, recommendations associated with the installation and inspection of bonding and grounding connections.

Since bonding and grounding are very closely related to many other aspects of system development and specifications covering a number of these have already been cited, applicable installation/inspection procedures previously stated will not be repeated, but the items and pertinent references will be listed. There are, however, several specific cases which have to be considered and, for these, applicable procedures are detailed.

Grounding and bonding connections are covered in Sections 8.4.6.1 and 8.4.6.2, respectively.

8.4.6.1 Installation/Inspection Procedures for System Grounding

The following procedures apply in connection with the installation and inspection of the grounding systems.

1. Grounding conductors and/or equipment grounding connections shall run directly to the system ground or made at the nearest internal grounding ring.
2. The minimum grounding conductor (or equivalent mechanical grounding connection) permitted under any condition is No. 6 AWG copper or equivalent. In many cases larger grounding conductors and/or more substantial grounding connections are mandatory; these are generally specified and installations should be made to conform.
3. Before assembling grounding connections remove all contaminants from the metal surfaces of parts to be joined.
4. In environments associated with nearby shock and/or vibration, protect the grounding system connections from physical damage and fatigue.
5. In exposed, corrosive environments grounding system connections should be protected by the treatments outlined in Section 5.2.2.3.2.

As an aid for checking during the installation/inspection stages of project development, Tables 8.1 and 8.2 list grounding connections within the power plant building and outlying facilities, respectively.

8.4.6.2 Installation/Inspection Procedures for System Bonding

Inspection requirements applying to all types of bonding for buildings, rooms, and equipment enclosures as well as to joints between sections of electrical raceway, bus enclosures, conduits, metal utility piping, ducts, plenums, cable troughs, etc. to insure that bonds between shielding elements are correctly made, are as follows:

1. all contaminants from the mating metal surfaces to be bonded have

Table 8.1

Grounding Connections In Power Plant Building

Items	Location	Connections	Conductor Size	Figure or Reference Section
Room Shielding with Steel Sheet	Control Room	Risers and Ground Ring	#6 Minimum	———
Frames of Electrical Equipment	Control Room	Ground Ring	#6 Minimum	5.2.2.3.6
Equipment Enclosures	Control Room	Ground Ring	#6 Minimum	5.2.2.3.9
Cable Trays (Also see Bonding Requirements)	Control Room	Ground Ring	#6 Minimum	5.2.2.3.7
Penetrating Conduits or Utility Piping	Control Room	Weld to Room	(#6) Equivalent	Figure 5.15 or 5.16
Penetrating Conduits or Utility Piping	Sheet Shielded Equipment Rooms	Weld to Room	(#6) Equivalent	Figure 5.15 or 5.16
Penetrating Conduits or Utility Piping Entering from Outside Building	Rebar or Welded Wire Fabric Shielded Areas	Grounding Plates and Possibly Wire Mesh Screens	Brazed or Welded	5.3.2.2
Penetrating Conduits or Utility Piping Bus Enclosures (All Voltages)	Unshielded Areas	Ground at Generators, Circuit Breaker Housings, and Internal Junction Boxes	Bolted	5.2.2.3.8
Conduits, Cable Sheaths, and Shields	Any	Ground at End Points to Ground Ring	#6 Minimum	5.2.2.3.7
Generator Neutrals	———	Connect to Neutral Grounding Equipment	———	5.2.2.3.8
Surge Sloping Capacitors	———	Connect Cases and Ground Terminals to Bus Enclosure or Cable Shields	———	5.2.2.3.8
Electrical Equipment Enclosures	Any	Grounding Conductor to Ground Ring	#6 Minimum	5.2.2.3.9
Neutral of Wye-Connected Transformers	Any	Follow Standard Grounded Neutral Distribution Practices	———	2.6.1, Item 4
Penetrating Metal Ducts and Plenums	Unshielded Areas	Ground at each End	———	2.11.2.8, Item 5
Building Shielding by Steel Sheet	Overall	Connections with Ground Rods	#6 Minimum	5.2.2.2
Building Shielding by Rebars or Welded Wire Fabric	Overall	Connections with Ground Rods	#6 Minimum	5.2.2.2
Rebar Used in Construction of Building	Throughout Building	Weld Outer Most Course of Rebars to Form Electrically Continuous Ground Conductor and Ground this Conductor	#6 minimum	5.2.2.2
All Sizeable Metal Objects (tanks, pumps, doors, etc.)	Any	Grounding Conductor to Ground Ring	#6 Minimum	5.2.2.3.6
Metal Sheaths of High Voltage Intertie Cables	Incoming Cable Vault	Ground Directly to Counterpoise or use Grounding Plates	Bolted, Brazed, or Welded Connections are Permissible	5.2.2.3.7 5.3.2.2
Surge Arresters	Incoming Cable Vault	Ground Directly to Counterpoise	#6 Minimum	3.6.1, Item 5
Transformer Cases	Incoming Cable Vault	Grounding Conductor to Internal Ground Ring	#6 Minimum	5.2.2.3.6

Table 8.2

Grounding Connections in Outlying Buildings and Facilities

Items	Location	Connections	Ground Size	Figure or Reference Section
Penetrating Conduits	Rebar or Welded Wire Fabric Shielding	Grounding Plates	Brazed or Welded	Figures 5.10 and 5.11
Above Ground Conduit Runs	Building Terminations	Interconnect with Counterpoise and Ground Rods	Brazed or Welded	3.1, Item 4
Above Ground Conduit Runs	Exiting>50ft. from Buildings	Connect to Driven Ground Rod	#6 Minimum	3.1, Item 4
Above Ground Conduit Runs	On Runs	Connect to 10' Ground Rods Every 100ft.	#6 Minimum	3.1, Item 4
Buried Conduit Runs	On Runs< 500ft. Long	Ground at Struture Penetrations	Brazed or Welded	3.1, Item 5
Buried Conduit Runs	On Runs>500ft. Long	Ground as Above and Ground Every 500' of Run	#6 Minimum	3.1, Item 5
Bus Enclosures (All Voltages)	Unshielded Areas	Grounded at Ends of Bus Runs	#6 Minimum	5.2.2.3.8
Cable Shields and Armor	Any	Ground at Terminating Enclosures	#6 Minimum	5.2.2.3.7
Conduit Runs to Outlying Facilities	Utility Tunnel	Ground to Tunnel Counterpoise at Penetrations	Brazed or Welded to Shielding	3.4, Item 4
Structural Steel (below ground level)	Utility Tunnel	Multiple Grounds to Tunnel Counterpoise	#6 Minimum	3.4, Item 3
Structural Steel (above or below ground level)	Outlying Buildings	Multiple Grounds to Building Counterpoise	#6 Minimum	5.2.2.2
Sheet Steel Shielding	Outlying Buildings	Multiple Grounds to Building Counterpoise	#6 Minimum	5.2.2.2
Conduits and Metal Utility Piping	Inside MSCB or DCCB	Internal Ground Ring or Direct to Counterpoise	#6 Minimum	5.2.2.3.7
Electrical Equipment and Enclosures	Inside MSCB or DCCB	Internal Ground Ring or Direct to Counterpoise	#6 Minimum	5.2.2.3.8
Lightning Masts and/or Air Terminals	Outlying Above Ground Buildings or Structures	Directly to Building Counterpoise	Minimum two #2	5.2.3.1.2
Manholes in Buried Conduit Runs>500'	Any	Supplementary 5 ohm Ground	Not Specified	Figure 5.8
Penetrating Conduits or Utility Piping	Sheet Shielded Areas	Continuous Weld to Room Shielding	(#6) Equivalent	Figures 5.15 and 5.16
Penetrating Utility Piping	Rebar or Welded Wire Fabric Shielding	Ground Plates and Possible Mesh Screens	Brazed, Welded	5.3.2.2.
Utility Piping	Non-hardened Areas	Direct Connection to nearest Internal Ground Ring	#6 Minimum	3.8, Item 3
Storage Tanks	Any	Multiple Grounds to Building Counterpoise	#6 Minimum	5.2.2.2
Security and Safety Gates	Any	Connect to Counterpoise under Gate	#2 Minimum	3.11, item 2
Security and Safety Fencing	Any	Connect to Ground Rods every 500ft. and at Corners	#6 Minimum	3.11, Item 1
Site Lighting Standards, 1 P Metal	Any	Connect to Building Steel, Adjacent Fencing, or Ground Rods	#6 Minimum	3.12, Item 2

been removed.

2. the bond was made by brazing, bolting, welding, or soldering.
3. in environments associated with vibration, flexible bonding connections are made.
4. bonding connections that are subjected to corrosive environments are treated with corrosion inhibitors. (The techniques outlined in Section 5.2.2.3.2 for grounding apply.)

Tables 8.3 and 8.4 list all system bonding recommendations for the power plant building and the outlying facilities, respectively.

8.5 Test/Evaluation of NEMP Protective Equipment

This section outlines specifications for quality assurance tests and evaluations to be made during the installation, operation, and maintenance phases. Such tests and evaluations fall in several different categories, including:

1. tests made in conjunction with the installation and/or the inspection of NEMP protective equipment.
2. final acceptance tests and evaluations performed in the field after the installation has been completed.
3. monitoring tests performed periodically after equipment reaches the operational stage.
4. tests and evaluations following repair or maintenance operations.

8.5.1 Test Methods and Specifications for Electrical Conduits and Fittings and Metal Utility Piping and Fittings

In the subsections that follow, specific techniques and procedures are described, acceptable test limits are stated, and application schedules are covered.

8.5.1.1 Conduit Discontinuity and Opening Detection Tests

The basic test setup for detection of conduit discontinuities is shown in Figure 8.1. The test locates and evaluates flaws in conduits and fittings or defective joints and discontinuities that would result in an

Table 8.3

Bonding Recommendations In Power Plant Building

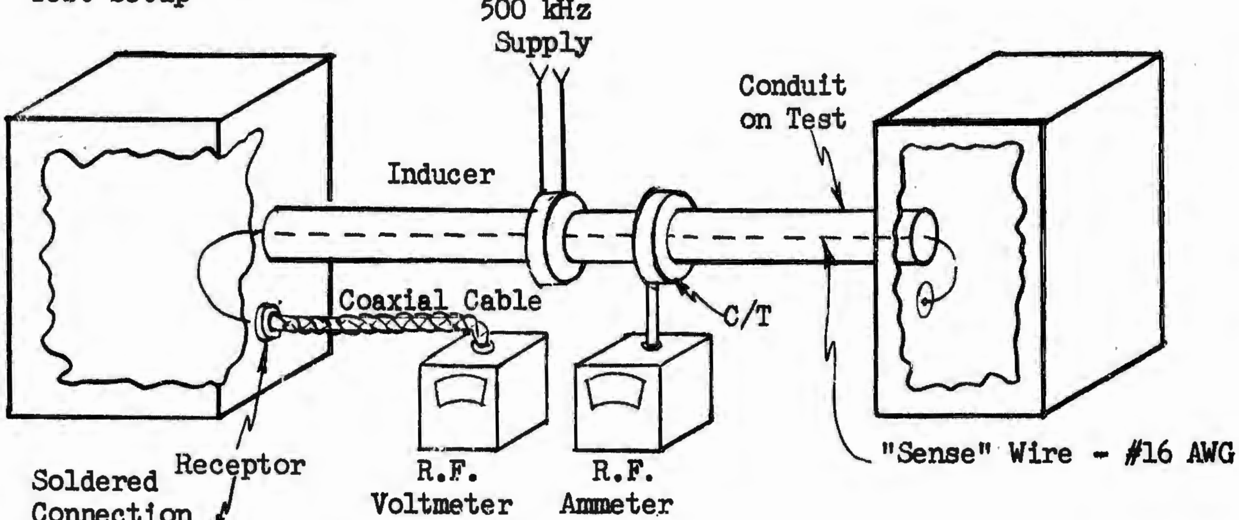
Items	Location	Recommended Bonding Method	Figure or Reference Section
Counterpoise Elements	Under Power Plant Building	Brazing	Figure 5. 1
Counterpoise to Ground Rods	Under Power Plant Building	Brazing	Figure 5. 1
Counterpoise to Risers	Under Power Plant Building	Brazing	8.3.2, Item 3
Risers to Internal Ground Rings	Rooms with Electrical Equipment	Brazing	Figure 5. 3
Connectors in Sections of Internal Ground Ring	Room with Electrical Equipment	Mechanical Connector or Braze	Figure 5. 3
Cable Tray Sections	Shielded Control Room	Bolt Clean Contacting Meta' Surfaces	2.1
Flexible Tubing Penetrating from Outside	Any type of Building Shielding	Flexible braided shunts Across Bellows	5.3.2.2
Rigid Conduits Penetrating from Outside	Sheet Steel Building Shielding	Continuous Weld	5.3.2.2
Rigid Conduits Penetrating from Outside	Rebar or Welded Wire Fabric Building Shielding	Continuous Welds to Plates and possibly Wire Mesh Screens	5.3.2.2
Rigid Conduits Penetrating from Outside	Unshielded Wall	Cadweld	Figure 5.14
Rigid Conduits Penetrating from Outside	Rebar or Welded Wire Fabric Wall Shielding	Cadweld	Figure 5.14
Rigid Conduits Penetrating from Inside	Rebar or Welded Wire Fabric Wall Shielding	Cadweld	Figure 5.16
Cable Shields and/or Metal Cable Armor	All Terminations	Bond to Terminating Enclosure	5.2.2.3.7
Bus Enclosure Sections (All Voltages)	Any	Bolt Clean Contacting Metal Surfaces	8.4.3.3, Item 3
Metal Duct or Plenum Sections	Any	Bolt Clean Contacting Metal Surfaces	5.2.2.3.6
Metal Wall Sleeve	Any Building Shielding Penetration	Weld to Plate Covering Opening	Figure 5.14

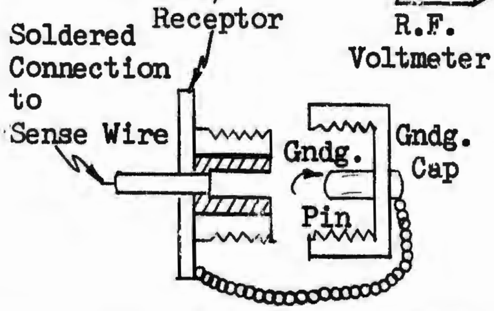
Table 8.4

Bonding Recommendations In Outlying Buildings and Facilities

Items	Location	Recommended Bonding Method	Figure or Reference Section
Interfaces of Conduits with Manholes and Handholes	Any	Continuously Welded Joint	8.4.1, Item 10
Interfaces of Conduits with Conduit Splice Boxes	Any	Continuously Welded Joint	8.4.1, Item 10
Interfaces of Conduits with Junction or Pull Boxes	Any	Double Locknuts—Nipple Fittings —Retained Conductive Gaskets	8.4.1, Item 10
Discontinuities in Metal Utility Piping	Any	Weld or Braze	5.2.2.3.11
Cable Shields and/or Metal Cable Armor	All Terminations	Bond to Terminating Enclosure	5.2.2.3.7
Bus Enclosure Sections (All Voltages)	Any	Bolting of Clean Contacting Surfaces	8.4.3.3, Item 3
Metal or Metal Shielded Roofing	Any	Bond All Roofing Sections	5.2.3.1.1
Metal or Metal Shielded Roofing	Any	Bond Edge to Nearest External Counterpoise	5.2.3.1.1
Metal Gravel Stops on Roofing	Any	Bond Stops to Roofing	5.2.3.1.1
Metal Clad Buildings	Any	Multiple Bond Roof to Sidewalls	5.2.3.1.1
Security and Safety Gates	Any	Bond to Adjacent Fencing	3.11, Item 3
Metal Duct or Plenum Sections	Any	Bolting of Clean Contacting Surfaces	5.2.2.3.6
Metal Wall Sleeve	Building Shielding Penetrations	Weld to Plate Covering Opening	Figure 5.14

Test Setup

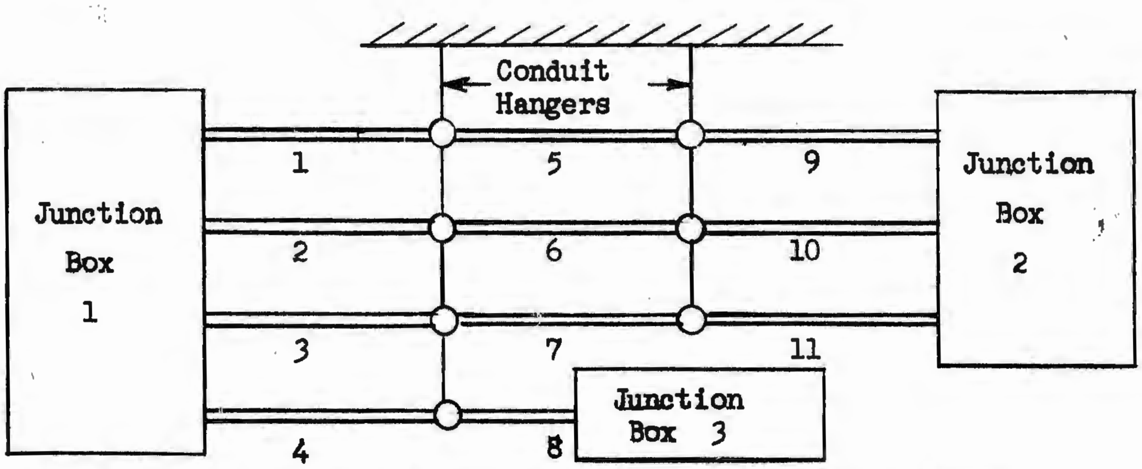




Receptor: Amphenol 83-798 or equivalent

Cap and Chain: Amphenol 83-1AC or equivalent. Modified to ground sensing wire.

Details of R.F. Receptor Terminal and Grounding Cap



Test Set Locations for Individual Tests of a Group of Conduits

FIGURE 8.1 Arrangements for Condult Discontinuity Detection Testing

attenuation loss or shielding degradation with high intensity ambient fields and currents.

This test setup requires that a special insulated number 16 AWG "sense" wire be permanently installed in each conduit run and terminated at the end of the run as shown in Figure 8.1. The test consists of circulating a 500 kHz current in the conduit by means of a portable test set which includes the RF source, current inducer to couple the current onto the conduit, current transformer to measure the conduit current, and an RF voltmeter to measure the voltage induced in the sense wire.

When making a conduit discontinuity test/evaluation, the following procedure is recommended:

1. Remove the grounding device at one terminus of the sensing circuit.
2. Check the sensing circuit for continuity using an ohmmeter or buzzer set.
3. If the sensing circuit is intact, connect it to the RF voltmeter.
4. Circulate a 500 kHz high frequency current through the conduit and measure its amplitude.
5. While maintaining the test current, read and record the voltage induced in the sensing wire.
6. Calculate the ratio of millivolts induced in the sensing wire to amperes circulated through the conduit on test.
7. Evaluate. As criteria, intact conduits, regardless of length or trade size, shall test not more than ten millivolts per ampere at a frequency of 500 kHz. Values exceeding 10 mV/A @ 500 kHz are indicative of conduit defects and maintenance should be scheduled.
8. After conducting the test, remove the access lead and replace the grounding device at the terminus of the sensing circuit.

Although the criterion for acceptable shielding is equal or less than 10 mV/A @ 500 kHz, this should not be taken to mean that high frequency currents of the order of amperes need be circulated. Actually, the test is as

feasible for high circulating currents with relatively insensitive detection system as it is for moderate circulating currents (order of milliamperes) with reasonably sensitive detection systems.

8.5.1.2 Schedules for Conduit Discontinuity Tests

Conduit discontinuity tests shall be made to assure quality shielding by conduits and fittings in accordance with the following schedule:

1. In connection with conduit subsystem acceptance after all conduit runs and wiring are in place. Readings of the induced voltage per ampere of test current should be recorded by conduit run to form a basis of comparison for later discontinuity detection tests. Any leaks and/or discontinuities must be located and repaired before coatings are applied.
2. Periodically, for monitoring the conduit subsystem after it becomes operational. Under normal conditions tests should be performed annually.
3. In connection with maintenance, system modifications and/or repair operations, including:
   a. relocation of existing conduits.
   b. additions or removal of conduits.
   c. any operation requiring removal or replacement of any wiring within conduits.
   d. any repair or maintenance work that involves disturbance of existing joints and fittings.

8.5.1.3 Metal Utility Piping Continuity Checks

If conscientiously followed, the inspection procedures specified in Section 8.4.1, Item 11 will suffice in lieu of electrical tests to establish the continuity of metal utility piping. It will be necessary, however, to conduct electrical tests on all bonding and grounding connections, as prescribed in Section 8.5.1.4.4.

8.5.1.4 Miscellaneous Tests on Conduits and Metal Utility Piping

The miscellaneous test procedures described below include those for:

1. Magnaflux (or equivalent) magnetic particle tests.
2. Ducter (or equivalent) tests.

Details of these tests, their applications, and recommended schedules are as follows:

8.5.1.4.1 Magnaflux (Magnetic Particle) Tests

Magnetic particle testing affords a convenient means for detecting internal defects in weldments such as seams, blowholes (porosity), inclusions, and cracks. The method is rapid, non-destructive, and relatively sensitive provided the surface of the weld is smooth.

The Magnaflux test has been used very successfully to determine the presence of both internal and surface defects in welds. Properly applied, the test accurately reveals defects such as cracks, lack of penetration, and inclusions to a depth of 1/4 inch below the surface of the weld. (Defects as deep as 3/8 inch below the surface are also indicated, but with less precision.)

Magnetization of the weld on test is accomplished by passing electric current through it or by the influence of an external magnetic yoke. Small local poles will be produced at the extreme edges of defects. These can be indicated and the location preserved by covering the surface with iron dust. This can either be applied dry or flowed on as a suspension in oil, water, or any suitable vehicle. At the local poles formed by discontinuities in the metal, the magnetization causes the iron dust to concentrate, revealing the location and shape of the defects.

The criterion for a satisfactory weld is that no visible concentrations of the magnetic medium shall appear on the weld on test.

8.5.1.4.2 Applications and Schedules for Magnetic Particle Tests

1. Magnaflux (or equivalent) tests shall be conducted on a random sampling of 5% of the welds (if used) in buried conduit runs before the application of coatings. Every welding defect shall be reported and corrected. If the prevalence of welding defects

in the samples tested exceeds five per cent, then another sampling of the original welds shall be tested. It shall be the decision of the designer to determine the final percentage of welds to be checked.

2. Magnaflux (or equivalent) tests shall be conducted on every weld at conduit or piping penetrations of sheet steel shielded buildings before the application of corrosion inhibiting coatings.
3. Magnaflux (or equivalent) tests shall be conducted on every weld at conduit or piping interfaces with room shielding.
4. Welding checks made at the time of initial installation and inspection are valid as final acceptance tests, provided all conduits and pipes were in place and no alterations were subsequently made.
5. Spot checks of accessible weldments should be made on an annual basis.
6. As a routine matter, all welds made in the course of maintenance of the conduit subsystem in connection with modifications and/or repair operations shall be subjected to magnetic particle tests and all welds found to be defective shall be corrected.

8.5.1.4.3 Ducter (or equivalent) Low Resistance Tests

Low resistance connections to conduits and metal utility piping are required to assure proper bonding and grounding.

Low resistances can conveniently be measured by use of specialized instruments such as the Biddle Ducter or Kelvin Double Bridge. These are applicable and accurate in the microohm range.

The Kelvin Double Bridge is portable and self-contained (battery operated). The Ducter is also portable, but requires an external ac supply to operate its drive motor. Both instruments utilize two double contact probes which are connected across the resistance to be measured. This arrangement minimizes the effect of contact resistance in the current circuit. A number of multiplier combinations are normally incorporated in the

design to extend the range of measurements.

When measuring resistances across welded, brazed, or bolted connections, a uniform separation of the two probes results in the most accurate readout.

8.5.1.4.4 Applications and Schedules for Low Resistance Tests

1. Ducter (or equivalent) low resistance tests shall be conducted on bonding and grounding connections. The measured resistance of an acceptable connection shall not exceed forty milliohms.
2. Low resistance tests made at the time of initial installation and inspection are valid as final acceptance tests provided all bonds and grounding connections were in place and no alterations were subsequently made.
3. Retests of all accessible grounding and bonding connections shall be made periodically, preferably on an annual basis. Deterioration of such connections should be carefully monitored and maintenance should be scheduled if the resistance limit in (1) above is exceeded.
4. Low resistance tests shall be conducted on all bonding and grounding connections disassembled and remade during maintenance and/or repair operations. Also, all new connections associated with system modifications shall be checked. The test limit prescribed in (1) above applies.

8.5.2 Test Procedures and Evaluation Specifications for Shielded Rooms and Shielded Equipment Enclosures

The recommended technique for testing the attenuation of shielded rooms and shielded equipment enclosures is based on a proposed IEEE standard.

This test is particularly adaptable to rectangular enclosures with edge dimensions of five to fifty feet and can be conducted after the enclosures are installed with all penetrations, openings, and equipment in place. The test instruments required are largely conventional and can be hand-carried to the test location.

The basic setup for a shielded enclosure test is shown in Figure 8.2. The magnetic field is generated by RF current through a large planar loop of wire encircling the enclosure, spaced by insulating blocks at least one inch away from the outer shielding surfaces. The loop, consisting of a single turn of insulated #18 AWG stranded copper wire, should be oriented at an angle to all enclosure surfaces as shown.

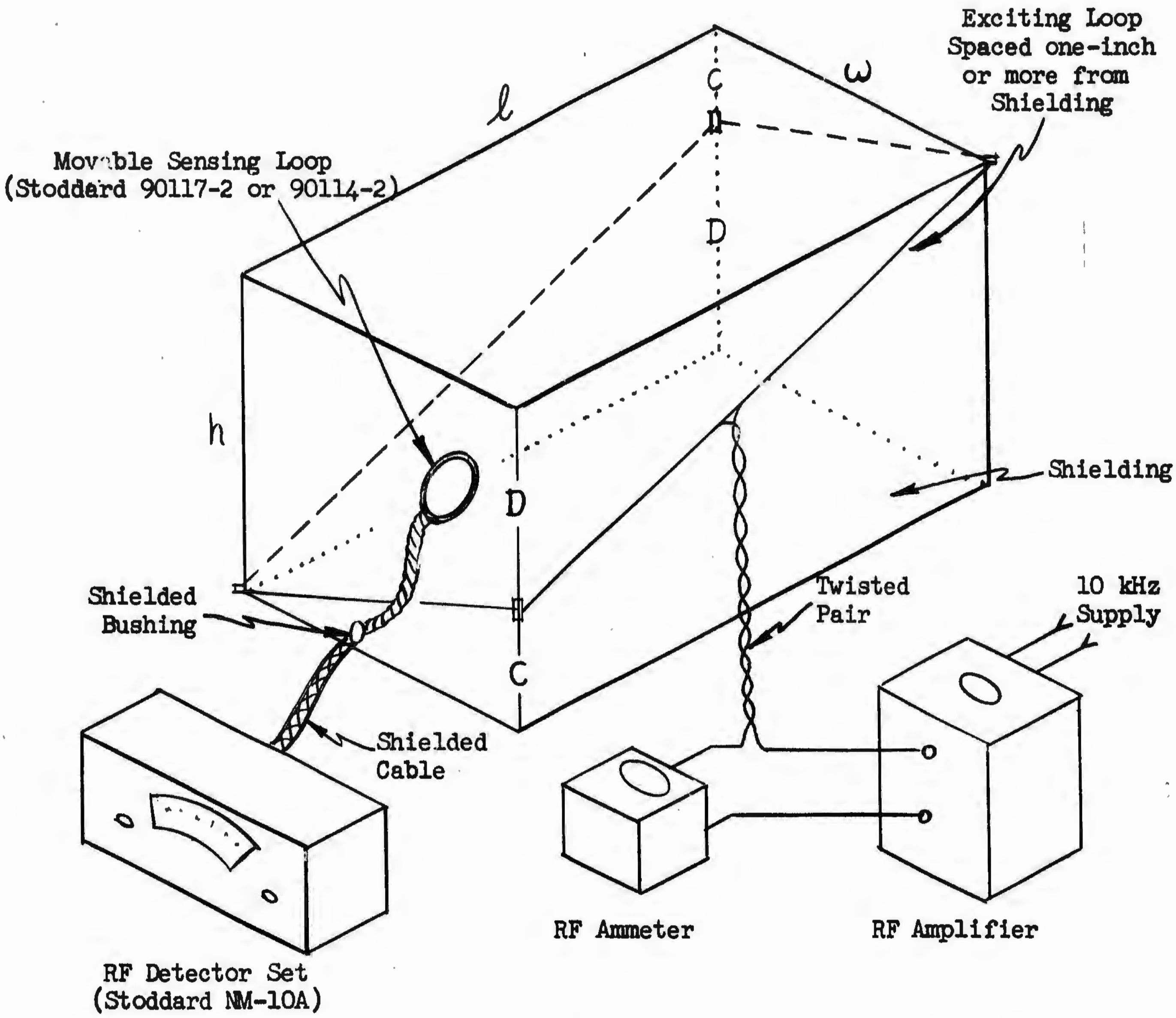
The amplified output of any stable, continuous wave RF source, such as an oscillator may be used to excite the loop. Generally, the amplifier output impedance is selected to match the loop impedance. The loop current should be monitored by a suitable RF ammeter or by measuring the voltage drop across a known carbon resistor in series with a loop supply lead.

The sensing loop diameter and number of turns will be governed by the sensitivity of the available detection equipment and by the available space within the enclosure for changing sensing loop positions.

Either conventional field strength meters or RF voltmeters capable of resolving 300 microvolts are suitable as detectors.

When making an evaluation of shielding attenuation the following procedure is required.

1. Install the exciting loop and set up the test equipment as shown in Figure 8.2.
2. Extend the shielded leads from the sensing loop outside the enclosure to the detection device.
3. Initially mount the sensing loop in the same plane as the exciting loop and as close to it as possible.
4. Energize the exciting loop and the detector and adjust the excitation current until a measureable readout is observed at the detector.
5. While maintaining the frequency and the magnitude of the current through the exciting loop, successively reposition and reorient the sensing loop within the enclosure until a maximum reading is



$$C = \left(\frac{w}{l + w}\right) h \qquad C + D = h$$

$$D = \left(\frac{l}{l + w}\right) h$$

Support exciting loop on standoff insulators. Provide slack in sensing loop cable to permit field evaluations anywhere inside enclosure.

FIGURE 8.2 Test Arrangement for Evaluation of Shielded Rooms and Equipment Enclosures

obtained. Record this maximum reading and its location.

6. Accurately measure the dimensions of the exciting loop while in place on the enclosure. Then remove the loop and set it up, preferably in a horizontal plane in an area clear of nearby objects.
7. Mount the sensing loop in the exact center of the exciting loop and align it to be in the same plane as the exciting loop.
8. Reconnect the leads to both loops and again energize the exciting loop at the frequency and current magnitude of Step 5.
9. Read and record the magnitude of the field strength or voltage coupled into the sensing loop without shielding.
10. Evaluate the shielding attenuation. Determine the shielding ratio by dividing the unshielded quantity read in Step 9 by the maximum shielded quantity read in Step 5. Then:

$$dB = 20 \log_{10} \frac{\text{RF voltage unshielded}}{\text{RF voltage shielded}}$$

11. Compare the shielding attenuation with minimum required levels. If the requirements are not met, the defects must be located and corrected.

8.6 Maintenance of NEMP Protective Equipment

8.6.1 Maintenance Procedures for Electrical Conduits and Fittings

8.6.1.1 Correction of Discontinuities and Other Defects

1. Follow up periodic discontinuity checks prescribed in Sections 8.5.1.1 and 8.5.1.2 to precisely locate any shielding defects. this may require additional tests with shielding discontinuity detectors.
2. Repair defects.
3. Recheck in accordance with Sections 8.5.1.1 and 8.5.1.2.

8.6.1.2 Correction of Deficiencies in Bonding Connections

Bonding maintenance involves the repair of faulty grounding connections. The following procedures apply:

9.0 EMP PROTECTION EVALUATION TECHNIQUES AND PROCEDURES

Analyses involving EMP protection techniques and procedures should include the following factors:

1. identification of significant EMP protection design requirements.
2. determination of alternative techniques and procedures to meet EMP protection design requirements.
3. development of comparative cost evaluation data based upon the techniques and procedures determined above.
4. choice of the most logical protection design weighing cost against adequacy of protection.

Techniques and procedures to meet the NEMP design requirements are given in Sections 2.0 and 3.0 of this report. Cost evaluation data, based on 1966 estimates, to implement the protection requirements given in Section 2.0 are listed in Table 9.1 for a power building. This cost evaluation does not consider the effects of possible commercial electric utility interconnection.

TABLE 9.1

POWER BUILDING EMP PROTECTION COST EVALUATION DATA

Criteria Requirement Reference Section	Evaluation Considerations	Estimated or Relative Cost
2.1 Control Room Shielding		
2.1.1	Different shielding attenuations are required. For metal skinned commercial shielded rooms, costs are approximately equal.	$\$25 \times 10^3$ est.
2.1.2		$\$25 \times 10^3$ est.
2.1.3		$\$25 \times 10^3$ est.
2.2 Conduits		
2.2.1	Rigid steel	1.0 rc
2.2.2	EMT (or aluminum)	0.7 rc

Table 9.1 (cont.)

Criteria Requirement Reference Section	Evaluation Considerations	Estimated or Relative Cost
2.1 and 2.2 Cable Trays	Permitted only with overall metal shield.	0.75 rc
2.3 Wiring		
2.3.1	Major differences are covered in Sections 2.2.1 and 2.2.2 under Conduits.	1.0 rc
2.3.2		1.0 rc
2.4 Electrical Equipment		
2.4.1	Differences are in integral shielding of equipments.	1.10 rc
2.4.2		1.05 rc
2.4.3		1.0 rc
2.5 Enclosures		
2.5.1	Differences are in shielding attenuation requirements.	1.10 rc
2.5.2		1.05 rc
2.5.3		1.0 rc
2.6 Grounding		
2.6.1	Complete grounding system installed concurrently with building construction.	$10 x 10^3$ est.
2.7 Openings		
2.7.1	Cost of air, exhaust and personnel openings in structure assumed as	
	Reference Cost (no shield)	$0.0 est.
	Overall Metal Shielding	$54 x 10^3$ est.
	Special Rebar Shielding	$54 x 10^3$ est.
	Welded Wire Fabric Shielding	$54 x 10^3$ est.

Table 9.1 (cont.)

Criteria Requirement Reference Section	Evaluation Considerations	Estimated or Relative Cost
2.8 Penetrations		
2.8.1	Cost of electric conduit penetrations in structure, assumed as	
	Reference Cost (no shield)	1.0 rc
	Overall Metal Shielding	0.8 rc
	Special Rebar Shielding	1.0 rc
	Welded Wire Fabric Shielding	1.0 rc
2.9 Utility Piping		
2.9.1	Same as Penetrations above.	
2.10 Overall Building Shielding		
2.10.1	No building shielding	
2.10.2	Welded wire fabric (6 x 6 - 10/10) @ $0.15 per sq. ft.	$21 x 10^3 est.
2.10.2	Special rebar welding @ $0.50 per sq. ft.	$70 x 10^3 est.
2.11.3	Overall metal shielding (MSR power building) with 1/8" steel plate @ $1.70 per sq. ft.	$238 x 10^3 est.

The cost data given above were obtained from "Building Construction Cost Data 1966", published by Robert Snow Means Company, Inc., Duxbury, Massachusetts and the Bechtel Corporation, Power and Industrial Division, Vernon, California. At this time it is not possible to estimate the total costs of conduits, wiring, electrical equipment, and equipment enclosures. In the table, therefore, only relative costs have been given for those items.

These relative costs are quite useful in that they make it possible to evaluate alternative shielding methods such as adding an overall metal shield and consequently substituting cable tray or EMT construction for conduits.

As an example of the usefulness of the data in Table 9.1, a cost comparison and cost evaluation of protection requirements, based on the most restrictive performance requirements and severest site environment, is given in Table 9.2. This table is particularly oriented towards a power building because, for all environments being considered, there are no differences in the design criteria requirements for facilities. In order to present comparison data for other possible building shielding arrangements, overall metal, special rebar welding and welded wire fabric were considered. Comparison of the "overall metal shielding" column with the last column of Table 9.2 shows a cost advantage greatly in favor of "no building shield".

Another cost comparison can be made between the extremes given in Section 2.0 criteria requirements for system performance and site environment requirements. This comparison is made in Table 9.3 and shows only a small cost difference between the NEMP design requirements for the two grossly different combinations of performance and environment requirements.

TABLE 9.2

POWER BUILDING EMP PROTECTION COST COMPARISON

Criteria Requirement Reference Section	Overall Metal Plate Shield	Special Rebar Welding	Welded Wire Fabric	No Building Shield
2.1 Control Room 2.1.1	\$0.0	\$25 x 10^3	\$25 x 10^3	\$25 x 10^3
2.2 Conduits 2.2.1 2.2.2	0.7 rc	1.0 rc*	1.0 rc	1.0 rc
2.3 Wiring 2.3.1	1.0 rc	1.0 rc	1.0 rc	1.0 rc
2.4 Electrical Equipment 2.4.1 2.4.3	1.0 rc	1.0 rc	1.0 rc	1.1 rc
2.5 Enclosures 2.5.1 2.5.3	1.0 rc	1.0 rc	1.0 rc	1.1 rc
2.6 Grounding 2.6.1	less than \$10 x 10^3	\$10 x 10^3	\$10 x 10^3	\$10 x 10^3
2.7 Openings 2.7.1	\$54 x 10^3	\$54 x 10^3	\$54 x 10^3	\$0.0
2.8 Penetrations 2.8.1	0.8 rc	1.0 rc	1.0 rc	1.0 rc
Overall Building Shield	\$238 x 10^3	\$70 x 10^3	\$21 x 10^3	\$0.0

* rc = relative cost

TABLE 9.3

POWER BUILDING PROTECTION COSTS VERSUS
PERFORMANCE REQUIREMENTS AND ENVIRONMENT
(No Special Building Shield)

Criteria Requirement Reference Section	Cost Comparison	
	2% Bus Voltage 1000 A/meter	50% Bus Voltage 100 A/meter
2.1 Control Room		
2.1.1	$25 x 10^3$	
2.1.3		$20 x 10^3$
2.2 Conduits		
2.2.1	1.0 rc*	
2.2.2		0.7 rc
2.3 Wiring		
2.3.1	1.0 rc	
2.3.2		1.0 rc
2.4 Electrical Equipment		
2.4.1	1.05 rc	
2.4.3		1.0 rc
2.5 Enclosures		
2.5.1	1.05 rc	
2.5.3		1.0 rc
2.6 Grounding		
2.6.1	$10 x 10^3$	$10 x 10^3$
2.7 Openings		
2.7.1	1.0 rc	1.0 rc
2.8 Penetrations		
2.8.1	1.0 rc	1.0 rc

* rc = relative cost

10.0 SUPPLEMENTARY REFERENCE INFORMATION

10.1 Grounding

10.1.1 Grounding, Counterpoise, and Bonding

General requirements of a protective system with respect to grounding, counterpoises, and bonding are based on four considerations:

1. The unwanted current must be conducted into the earth along a controlled path.
2. The current path should have as low a resistance as practical and, to minimize inductance, should be as short and as direct as possible.
3. In areas where electrical equipment is located, a uniform potential ground plane should be established.
4. In areas frequented by personnel, so-called "touch" and "step" voltages should be prevented. These are the voltages that could exist between two pieces of equipment which an operator could simultaneously touch; or voltage differences that could exist between the point where a man is standing and equipment he could touch, or voltage differences that could exist between a man's feet.

The first step towards meeting the above requirements is to provide a controlled path to conduct current into the earth.

10.1.2 Ground Rods

Current through a resistance path between a point of entrance and the earth will produce a voltage drop that might be dangerous to personnel and equipment. At times, unwanted currents can be quite large; therefore, the resistance of the discharge path must be kept as small as possible. For this reason, structures or equipment that form part of a current discharge path are required to be electrically grounded; that is, have low resistance connections to earth. The resistance of such a current path is generally the sum of the resistances of the metallic structure or equipment and its joints, as well as the ground resistance. Usually, the ground resistance

is the largest component of resistance in a current path.

To understand what is meant by the term "ground resistance", certain underground electric current phenomena must be studied. The phenomenon of current conduction through the earth (a three-dimensional body) loses the simplicity of linear wires by which currents are usually directed. Further, the ground under the earth's surface is not homogeneous; this makes a rigorous analysis of the distribution of ground currents very difficult, if not impossible. However, a quantitative analysis of electric current phenomena in the ground is possible if homogeneity is assumed. Such an analysis will allow numerical calculations and permit definite conclusions to be drawn. The literature on ground resistance is extensive and needs little expansion. The purpose of the paragraphs that follow is simply to provide a capsule introduction to ground resistance.[5,6]

To better understand earth-current phenomena, a simple electrode in homogeneous earth will be considered. The meter-kilogram-second (MKS) system of units will be used for the analysis.

The simplest electrode, geometrically, is a hemisphere of radius (r meters) embedded in the earth as shown in Figure 10.1. If a current (I amperes) is passing through this electrode and spreading radially into the ground, the current density at a distance (x meters) from the center of the hemisphere is (J amperes/meter^2)

where:

$$J = \frac{I}{2 \pi x^2} \text{ amperes/meter}^2 \qquad (1)$$

According to Ohm's Law, such a current density produces an electric field strength (e volts/meter) because of the resistivity (ρ ohms-meter) of the earth, or

$$e = \rho i = \frac{\rho I}{2 \pi x^2} \text{ volts/meter} \qquad (2)$$

The voltage, as the line integral of the field strength from the surface of the conducting hemisphere out to any distance (x meters) is

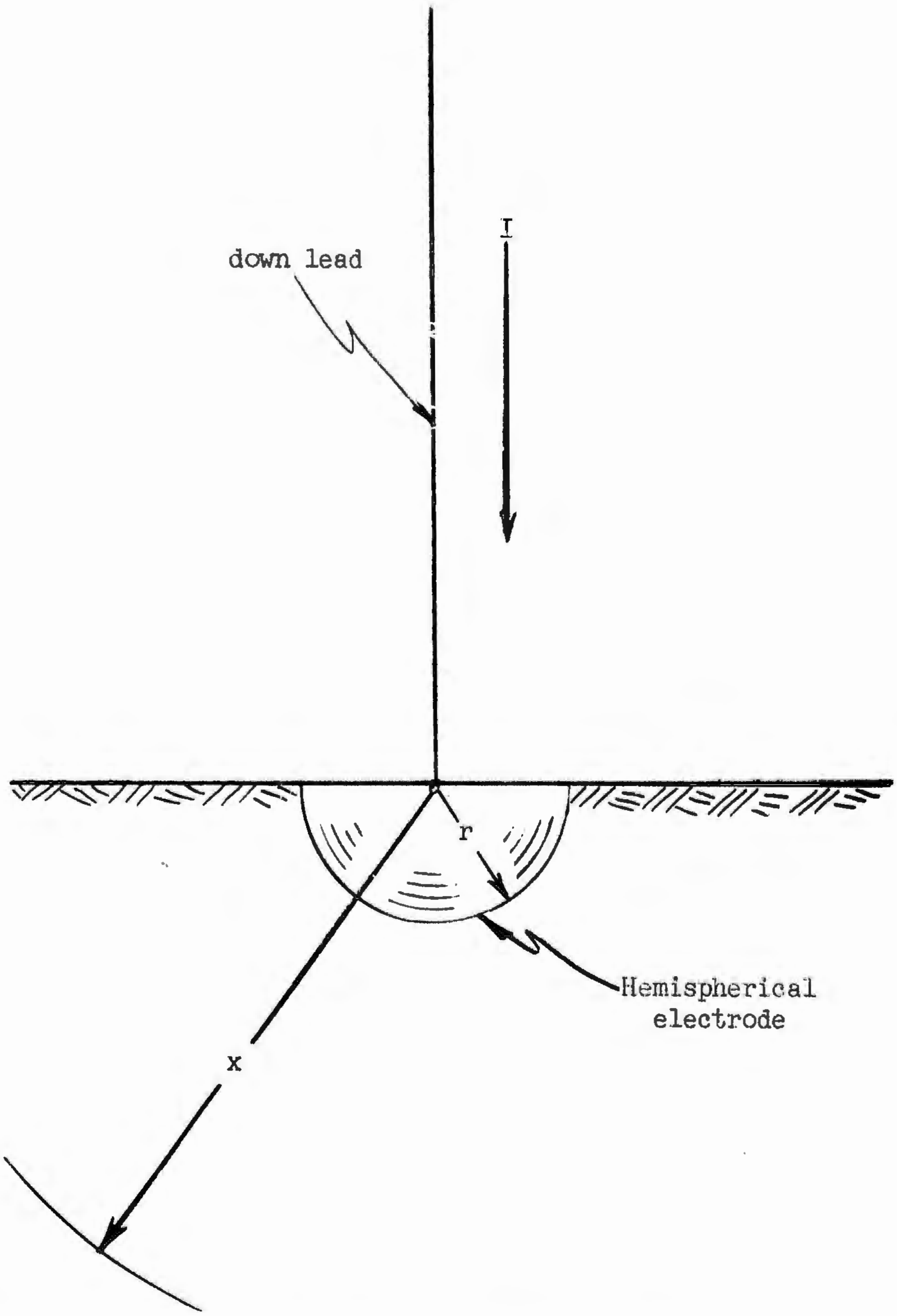


FIGURE 10.1 Hemispherical Electrode Embedded in the Earth

$$E = \int_r^x e\,dx = \frac{\rho I}{2\pi} \int_r^x \frac{dx}{x^2} = \frac{\rho I}{2\pi} \left(\frac{1}{r} - \frac{1}{x} \right) \qquad (3)$$

where r = radius of conducting hemisphere in meters.

The total voltage between the hemisphere and a far-distant point (x approaching infinity) is:

$$E = \frac{\rho I}{2 \pi r} \text{ volts} \qquad (4)$$

The total resistance offered by the multiplicity of current paths diverging from the hemisphere is then

$$R = \frac{E}{I} = \frac{\rho}{2 \pi r} \qquad (5)$$

As an example, a hemispherical electrode of radius (r) = 1 meter embedded in soil of resistivity ρ = 10 ohms-meter will have a ground resistance of

$$R = \frac{\rho}{2 \pi r} = \frac{10 \text{ ohms-meter}}{2 \pi \text{ (1 meter)}} = 1.6 \text{ ohms}$$

This is the resistance to the passage of electric current from the electrode to the entire surrounding space. Most of this resistance is encountered in the region immediately around the electrode because the surface area there is comparatively small. Analysis of Equation (3) shows that fifty percent of the total voltage drop resulting from the current through this resistance occurs between the surface of the electrode and a point at a distance (x = 2r), and that ninety percent of the drop occurs between the electrode and a point at a distance (x = 10r). For the example calculated, these distances are two meters and ten meters, respectively. The voltage gradient at point on the surface of the earth in proximity to a grounding electrode when carrying current, expressed as a percentage of the total electrode drop, is shown in Figure 10.2.

A significant potential difference can exist between two adjacent points; for example, between points "a" and "b" on the surface of the earth

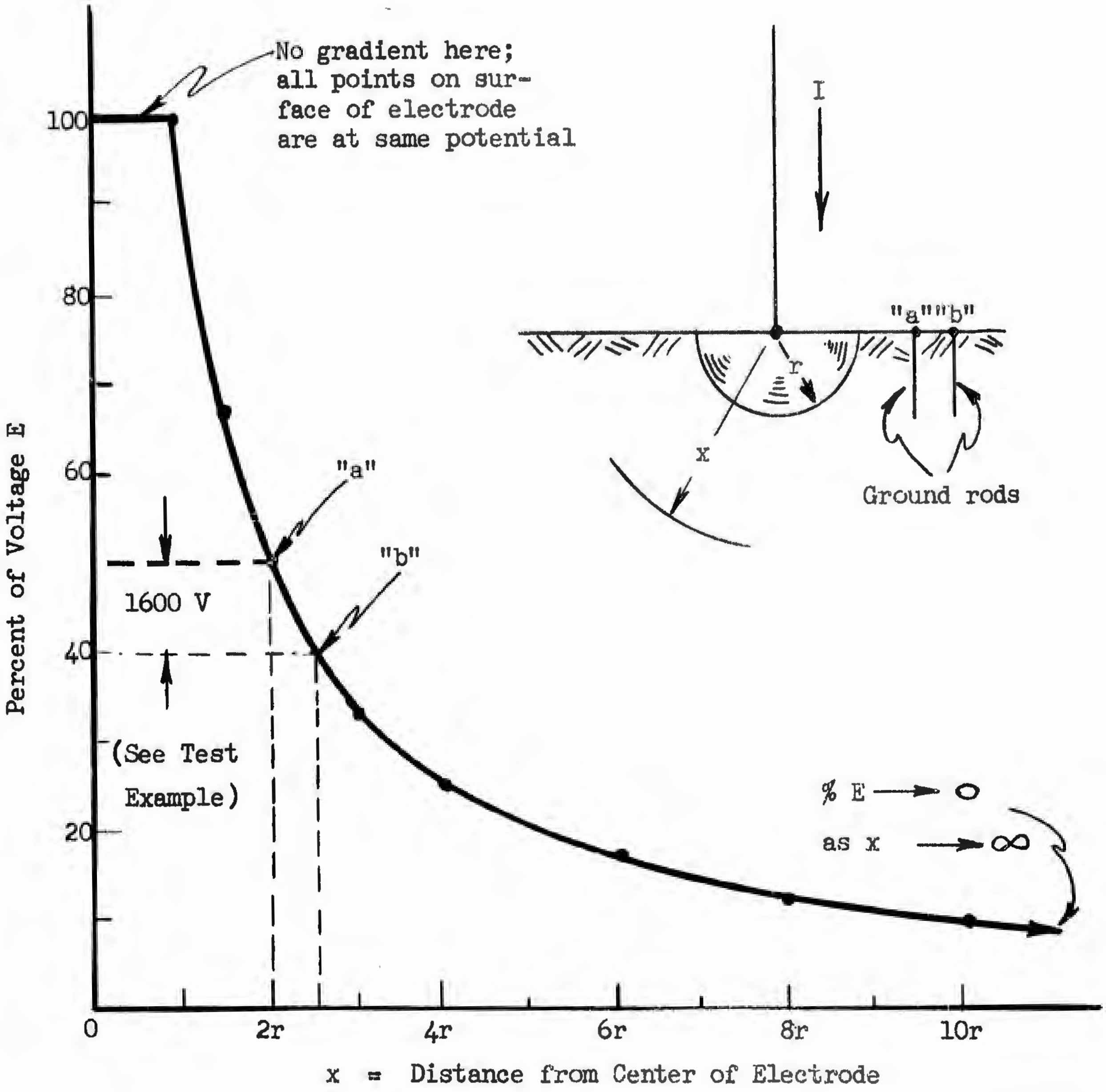


FIGURE 10.2 Voltage Gradient for a Hemispherical Electrode of Radius (r)

near a current-carrying grounding electrode with a radius of one meter and with a total ground resistance of 1.6 ohms. For a current of 10,000 amperes, the potential difference between point "a", at two meters from the center of the electrode, and point "b", at 2-1/2 meters from the center, is shown to be approximately 1600 volts.

Voltages of this order, existing between two points only one half meter apart on the surface of the earth can be harmful to people and electrical equipment.

Thus far, a simple hemispherical electrode has been used to illustrate the effects of ground resistance upon ground electrode potentials and the voltage gradient (potential difference) along the surface of the earth near a current-carrying ground electrode. Exactly the same phenomena occur with the more commonly used ground rod - an electrode having a length much greater than its diameter.

Ground rods usually come in 8 to 12 foot lengths which may be joined by couplings for driving to greater depths. Rod diameters are generally less than one inch. The resistance of a driven ground rod is, from Dwight[6] approximately

$$R = \frac{\rho}{2\pi \ell}\left[\left(2.303 \log \frac{4\ell}{r}\right) - 1\right]$$

where ρ = ground resistivity, in ohms-meter

ℓ = length of rod, in meters

r = radius of rod, in meters

Table 10.1, from Sunde[7], shows the variations in ground resistance with various rod lengths and diameters. Data for this table were obtained from Equation (6) using a ground resistivity ρ of 100 ohms-meter, assumed to be uniform for the depths to which the rod is driven. Actually, the ground resistivity would vary somewhat with depth, being less at permanent moisture levels than near the surface.

Inspection of Equation (6) and Table 10.1 shows the following:

1. Small diameter rods driven to practical depths are nearly as

effective for driven grounds as large diameter rods driven to the same depths. This is illustrated in Figure 10.3, chart A.

2. The depth to which a ground rod is driven is very important, up to practical limits. Since the ground resistance decreases exponentially with driven depth, driving a rod beyond a practical depth is accompanied by only a meager reduction in ground resistance. This is illustrated in Figure 10.3, chart B.
3. The ground resistance obtainable with a driven rod depends directly upon the average earth resistivity of the soil into which it is driven. Ground resistance may vary considerably with soil and moisture contents, as shown in Table 10.2 from Watt[8].

From the fact that the ground resistance varies directly with the earth resistivity, and from the data of Tables 10.1 and 10.2, the ground resistance of any ground rod can be quickly approximated. As an example, a 1/2-inch diameter rod driven ten feet into marine sand would offer a ground resistance between 0.35 ohm and 3.5 ohm, the actual value being predominantly affected by moisture content.

A nomogram relating the basic factors discussed above to the resistance developed with a single driven ground rod is presented in Figure 10.4. This is useful in quickly determining the ground resistance with variations in the parameters.

To illustrate the use of the nomogram it will be assumed that a single rod 5/8" in diameter is driven ten feet into soil having a uniform resistivity of 20 ohms-meter. To find the ground resistance, proceed as follows:

1. With a straightedge, align the 10-foot division on the length (L) scale with the 5/8" division on the diameter (d) scale, and mark the point at which the straightedge intersects the uncalibrated (q) scale.
2. Align this point with the 20 ohms-meter division on the resistivity (ρ) scale, and read out the corresponding ground resistance

TABLE 10.1

GROUND RESISTANCE (OHMS)* OF VARIOUS LENGTHS AND DIAMETERS OF DRIVEN GROUND RODS

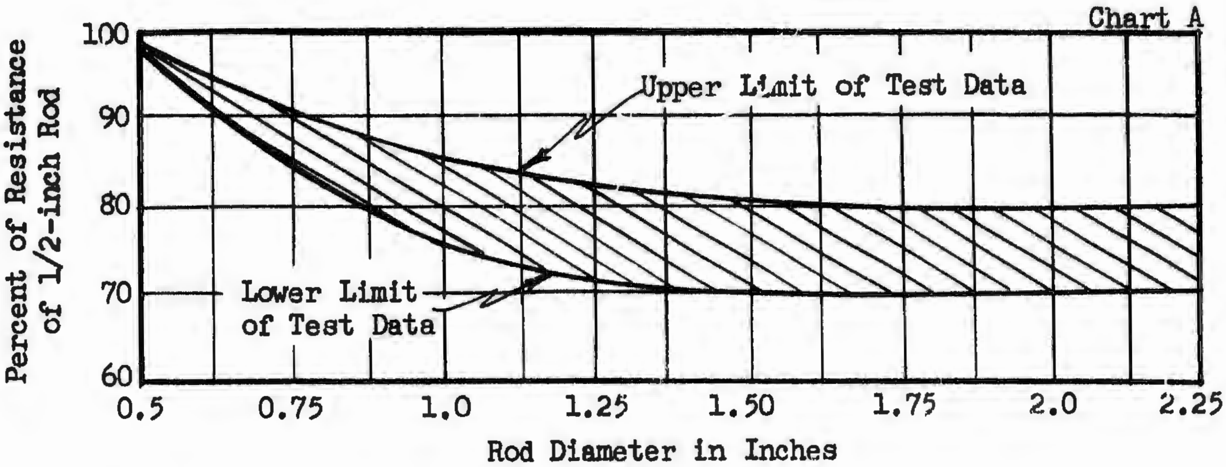
Ground Rod Diameter (inches)	Driven Depth of Ground Rod(s)						
	1 foot	2 feet	5 feet	10 feet	20 feet	50 feet	100 feet
0.5	225	132	62	35	19.2	8.7	4.7
1	188	113	55	31	17.3	8.0	4.3
2	151	95	47	28.5	15.5	7.2	4.0
4	115	77	40	25	13.6	6.5	3.6
12	69	51	28.5	18.1	10.9	5.4	3.0
24	44	35	21	14.4	9.0	4.6	2.6

* Based on earth resistivity (ρ = 100 ohms-meter)

TABLE 10.2

REPRESENTATIVE VALUES OF EARTH RESISTIVITY

Material		Approximate Resistivity (ohms-meter)
Soil	good	10 to 10^2
	average	10^2 to 10^3
	poor	10^3 to 10^4
Water	sea	0.2 to 0.25
	fresh	10^3 to 10^4
Sediments	marine sands and shales	1 to 10
	marine sandstones	1 to 10^2
	clay	10 to 10^2
	sandstone (wet)	10^2 to 10^4
	sandstone (dry)	10^4 to 10^7
	limestone	10^4 to 10^8
Igneous Rock	granite	10^3 to 10^9
	basalt	10^5 to 10^9
Metamorphic	slate	10^3 to 10^5
	marble	10^3 to 10^8
	gneiss	10^3 to 10^7
	serpentine	10^3 to 10^7



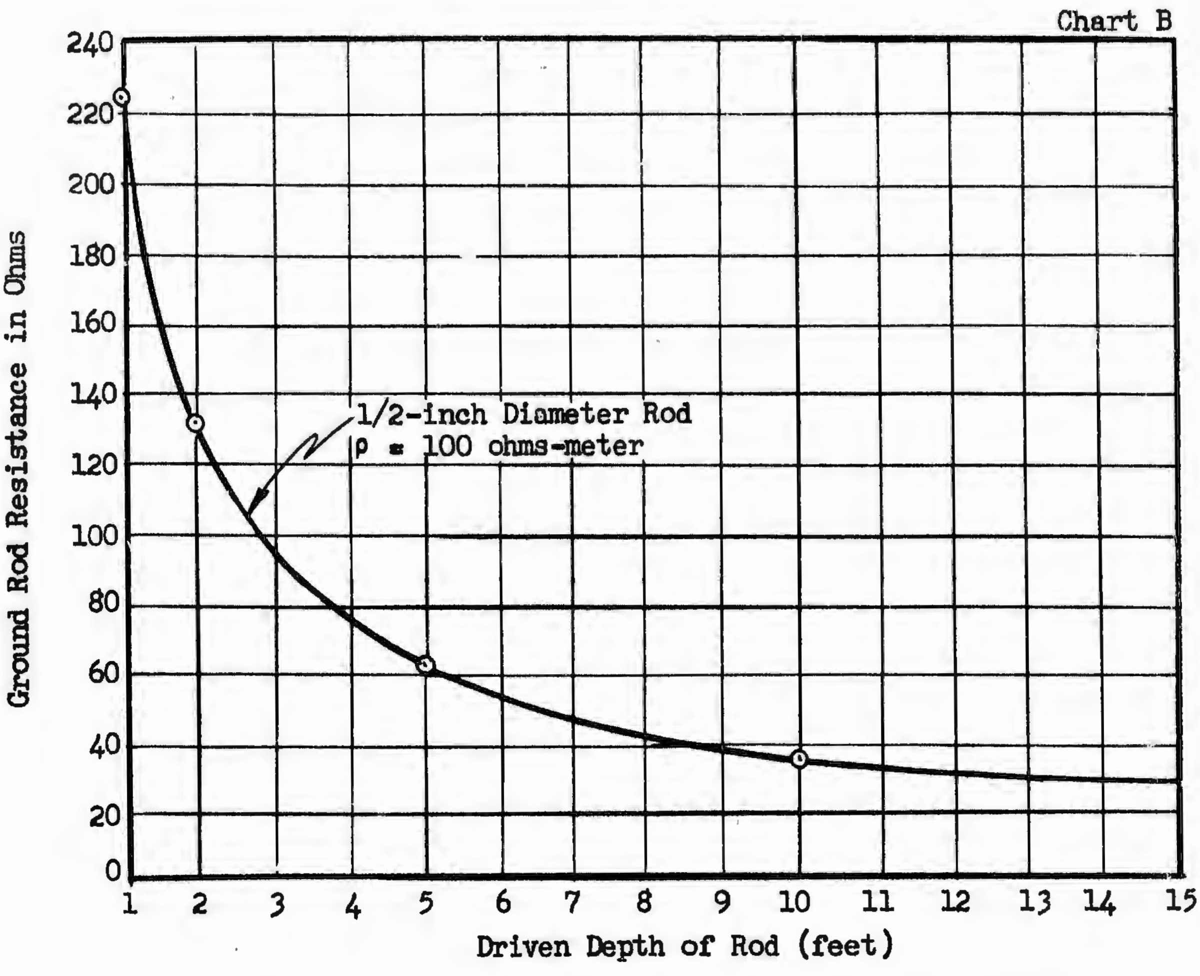


FIGURE 10.3 Effects of Ground Rod Diameter and Length upon Resistance of a Driven Rod

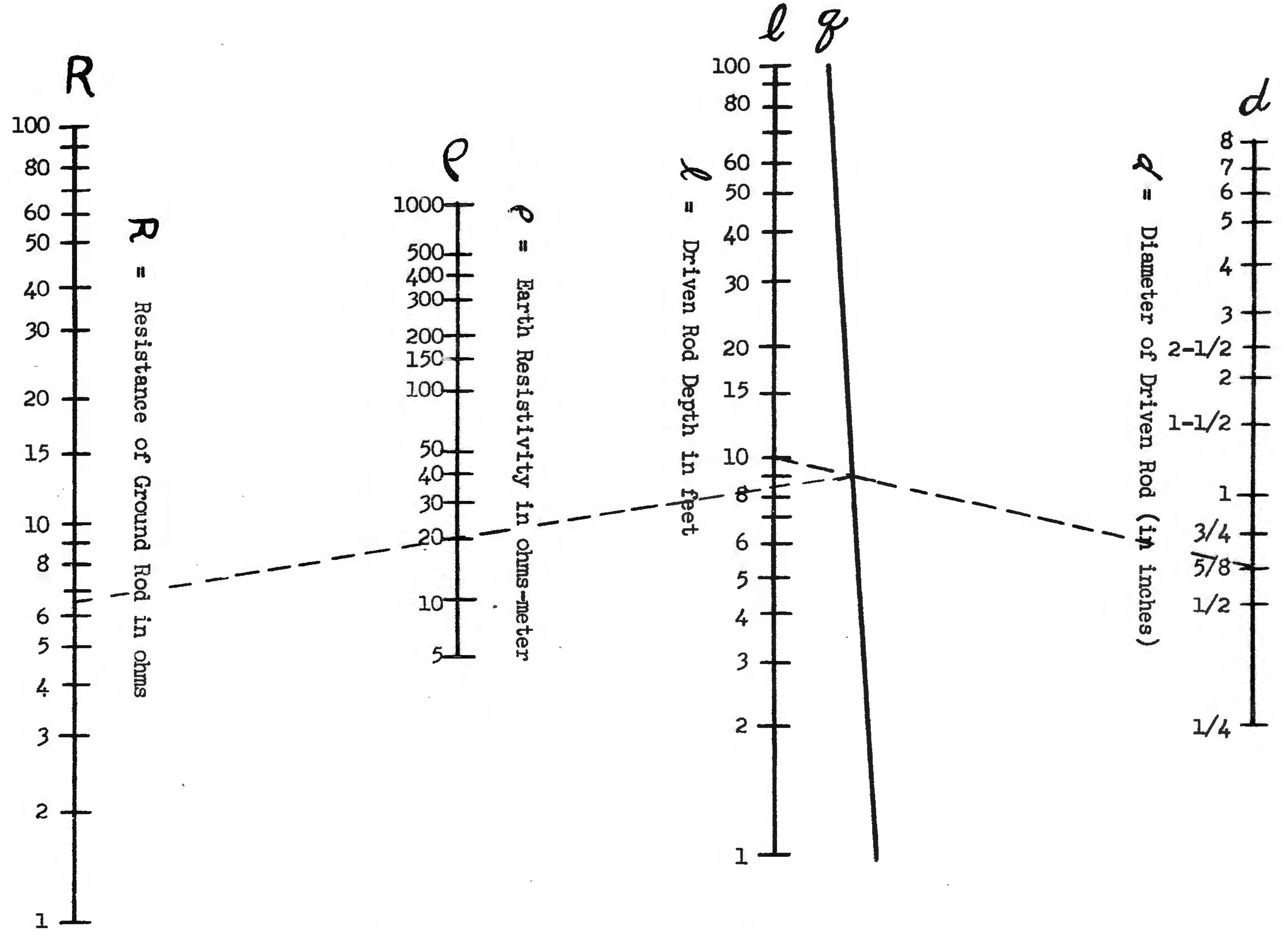


FIGURE 10.4 Nomogram Relating Factors Contributing to the Earth Resistance of a Single Driven Ground Rod

(6.6 ohms) on the R-scale.

Now suppose that the 6.6 ohm resistance must be reduced to 2.5 ohms to meet a specification. Two practical methods of reducing the rod resistance are possible.

The first involves reducing the earth resistivity by chemical treatment, retaining the 10 foot, 5/8" diameter rod. On the nomogram, align the desired resistance division, 2.5 on the R scale, with the mark on the q scale and read the resuired soil resistivity 7.5 ohms-meter on the ρ scale.

The second method requires driving the rod to a greater depth, assuming the original ground resistivity (20 ohms-meter). On the nomogram, align the 2.5 ohms division on the R scale with the 20 ohms-meter division on the ρ scale and mark the point of intersection of the straightedge on the q scale. Then align this point with the 5/8" division on the d scale and read the required rod length, 32 feet on the L scale.

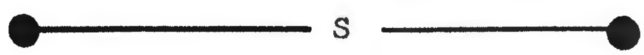
It is, of course, practical and possible to use a combination of these two methods to attain a required rod resistance; on the other hand, the nomogram discloses the impracticality of using a larger diameter rod, if the original length and earth resistivity could not be altered.

When it is not possible to obtain the desired ground resistance from a single ground rod, several ground rods may be driven and connected in parallel. If the spacing between rods is large compared to the driven depth of the individual rods, the ground resistance will be reduced in proportion to the number of rods. If, however, the rods are close together, each rod will be in the intense electrical field of its neighbor, and the ground resistance will not be reduced proportionately.

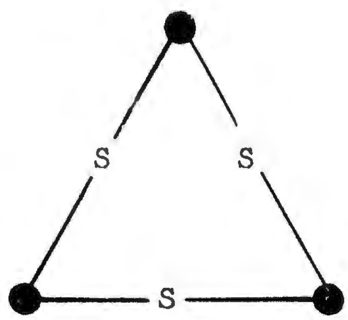
If the rods are very close together the overall resistance becomes:

$$R = \frac{2.303\,\rho}{2\,\pi\,\ell} \log \frac{2\,\ell}{A} \qquad (7)$$

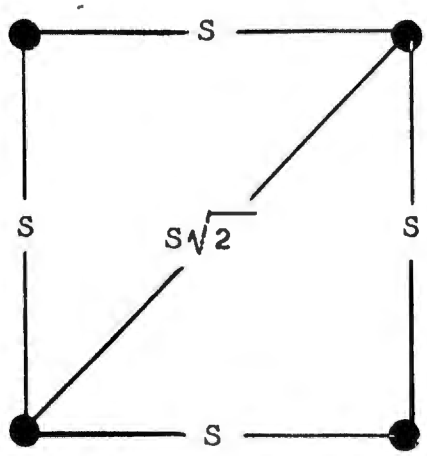
where A represents the radius of an equivalent rod. The expressions in Figure 10.5 show how the equivalent radius (A) depends on rod geometry.



$A = \sqrt{rS}$ (8)



$A = \sqrt{rS^2}$ (9)



$A = \sqrt[4]{rS^2\sqrt{2}}$ (10)

r denotes radius of indivisual rods

S denotes spacing of rods

A is calculated radius of equivalent rod

FIGURE 10.5 Equivalent Ground Rod Radius as a Function of Multiple Rod Geometry

In each case, "r" denotes the radius of the individual rods. If the rods are moderately close to each other, the overall resistance will be more than if the same number of rods were driven far apart. For instance, using Equations (7) and (8) with the necessary metric conversions, two 3/4 inch diameter, 10 foot rods in parallel, driven one foot apart in a soil of resistivity of 10 ohms-meter will have a resistance of 2.5 ohms. The same two rods driven ten feet apart in soil of the same resistivity will have a combined ground resistance of 1.9 ohms. Lewis[9] gives additional information on ground rods in parallel as a function of their spacing.

Appropriate to the topic of grounding is a short discussion on the measurement of ground resistance. The fundamental method of measuring ground resistance makes use of the basic connections shown in Figure 10.6. Current is circulated between the ground under test and an auxiliary ground. Preferably, this auxiliary ground should be located at a distance that is large compared to the dimensions of the ground under test, since it is not desirable to have interaction of the ground current distributions at the two electrodes. A voltage is then measured between the ground under test and a reference ground located somewhere between the two current-carrying electrodes. This reference ground should also be so located that it is not in the electric field of either of the current-carrying electrodes. Assuming that placement is such that the current density at the reference electrode is negligible, the resistance of the ground under test is:

$$R = \frac{V}{I}$$

where V is potential difference between the ground under test and the reference ground, and I is the current between the ground under test and the auxiliary ground.

The measurement may be made using a voltmeter and ammeter with current being supplied by a transformer energized from ac power lines. Alternately, a bridge may be used for the measurement. Most often, however, ground resistance is measured with self-contained instruments such as the James G. Biddle Company's "Megger" ground resistance tester.

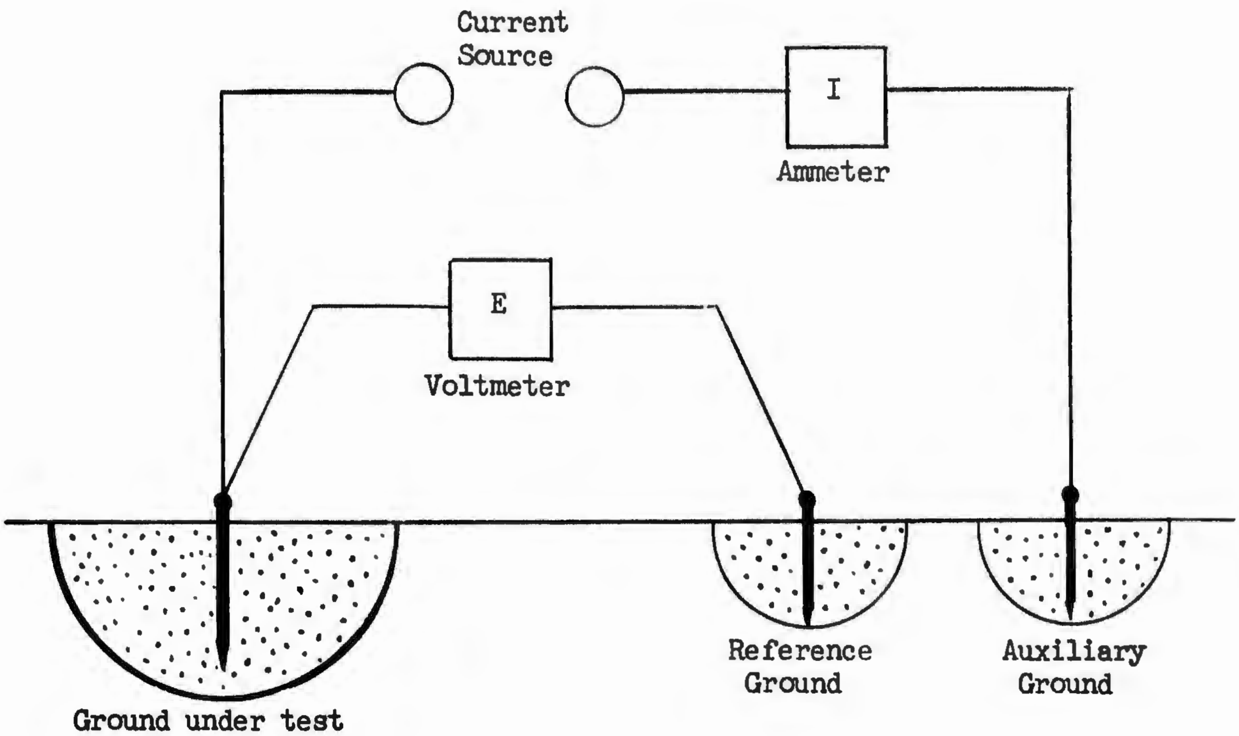


FIGURE 10.6 Basic Connections for Ground Resistance Measurement

When measuring the ground resistance of an extensive structure or a complex grounding system, it may be difficult to place the auxiliary current ground or the reference ground sufficiently far from the ground under test that the electric fields of the electrodes do not interact. Curdts[10] has shown that substantially the correct ground resistance is measured if the reference ground is placed at a point approximately 60 percent of the distance measured from the ground under test to the auxiliary ground. If the system is large, errors may be encountered as a result of stray currents in the ground from outside power sources. These will affect the accuracy of the ground resistance measurements under certain conditions. However, no such errors are introduced when using a self-contained ground tester, since the current frequency of the test set is generally different from the frequency of the interfering currents. Such interfering currents can also be balanced out in the measuring instrument. Duke and Smith[11] have described a sixty-cycle test set which contains such balancing circuits. This set is used for the measurement of low-impedance grounds.

10.1.3 Counterpoise

A counterpoise is a continuous bare wire, or a network of bare wires, buried in the ground parallel to the surface. The several functions of the counterpoise are as follows:

1. to reduce the resistance of grounding electrodes.
2. to interconnect grounding electrodes.
3. to provide a convenient means of grounding equipment and circuits.
4. to reduce voltage gradients at the earth's surface.
5. to "by-pass" undesired currents by conducting them away from the equipment and circuits being protected.

The resistance of a single buried horizontal wire is, from Section 3.6 of Sunde[7],

$$R = \frac{\rho}{\pi \ell}\left[\left(2.303 \log \frac{2\ell}{\sqrt{2\,rd}}\right) - 1\right] \qquad \text{when } d \ll \ell \qquad (11)$$

where l = length of wire, in meters

r = wire radius, in meters

d = burial depth, in meters

Table 10.3 shows how counterpoise resistance to the earth varies with buried length and depth.

Equation (11) assumes that the potential is uniform over the entire length of the counterpoise. If a counterpoise is very extensive, it will not be at the same potential all along its length and Equation (11) will not hold. However, from a practical viewpoint, the diameters and lengths of counterpoise conductor normally used are such that errors introduced by inherent counterpoise resistance may be neglected.

TABLE 10.3

RESISTANCE TO EARTH (OHMS)* OF HORIZONTAL GROUND WIRE** AT THE SURFACE AND AT A DEPTH OF 12 INCHES

	Ohms for Wire Length						
Burial Depth	10 feet	20 feet	50 feet	100 feet	200 feet	500 feet	1000 feet
0 - at surface	80	45	19.4	10.4	5.6	2.4	1.29
12 inches	47	27	12.8	7.1	3.9	1.75	0.95

* Based on soil resistivity of 100 ohms-meter

** Wire gauge - No. 10 AWG (.00127 meter radius)

Another consideration in determining the effective resistance to earth of a counterpoise is its transient response (surge impedance with respect to time) when it is conducting a current pulse. Initially, the effective resistance is relatively high - of the order of 150 ohms. This is defined as the "initial surge impedance". As the pulse propagates along the counterpoise and enters the earth, the surge impedance of the counterpoise decreases progressively, eventually reaching a steady-state condition of minimal resistance.

The surge propagates into the earth surrounding the counterpoise at

roughly one-third the speed of light. As an example, approximately three microseconds of time would be required for a current surge to traverse a 1000 foot length of counterpoise. For a given length of buried conductor, the transient response will reduce to the steady-state minimum resistance faster if the counterpoise is made of several short, radial conductors than if it is just one long wire. Figure 10.7 from Lewis[9] shows how the transient response of buried conductors varies with several counterpoise configurations. In the case of driven ground rods, the final resistance is attained quickly, since the rods are relatively short. (Widely-spaced ground rods cannot attain their ultimate, minimum resistance to earth until the current surge reaches the most distant rod.) As a practical matter for counterpoise application the first 250 feet of buried conductors are the most effective for grounding surge currents. This is brought out by Figure 10.7 which shows that a buried counterpoise of four radial elements (L = 250 feet per element) will attain an assumed impedance of ten ohms in less than two microseconds. The same amount of conductor arranged as a three-element counterpoise will attain the same impedance, but in a time of 2.5 microseconds. Corresponding times for two radial elements and a single element counterpoise are four microseconds and over ten microseconds, respectively. Assuming soil of the same resistivity, a greater length of counterpoise conductor buried deeper than the counterpoise of this example would produce lower ultimate effective impedances.

Ground resistance decreases with increasing current (until the current heats the soil moisture to the boiling point). The proportional reduction in resistance is less for grounds of low resistance than for grounds of high resistance. Figure 10.8, from Lewis[9], shows typical measured values of ground resistance as a function of various impulse currents.

10.1.4 Bonding[12]

Bonding is defined as providing connections between parts that must be electrically continuous, such as mechanical joints in metallic structures,

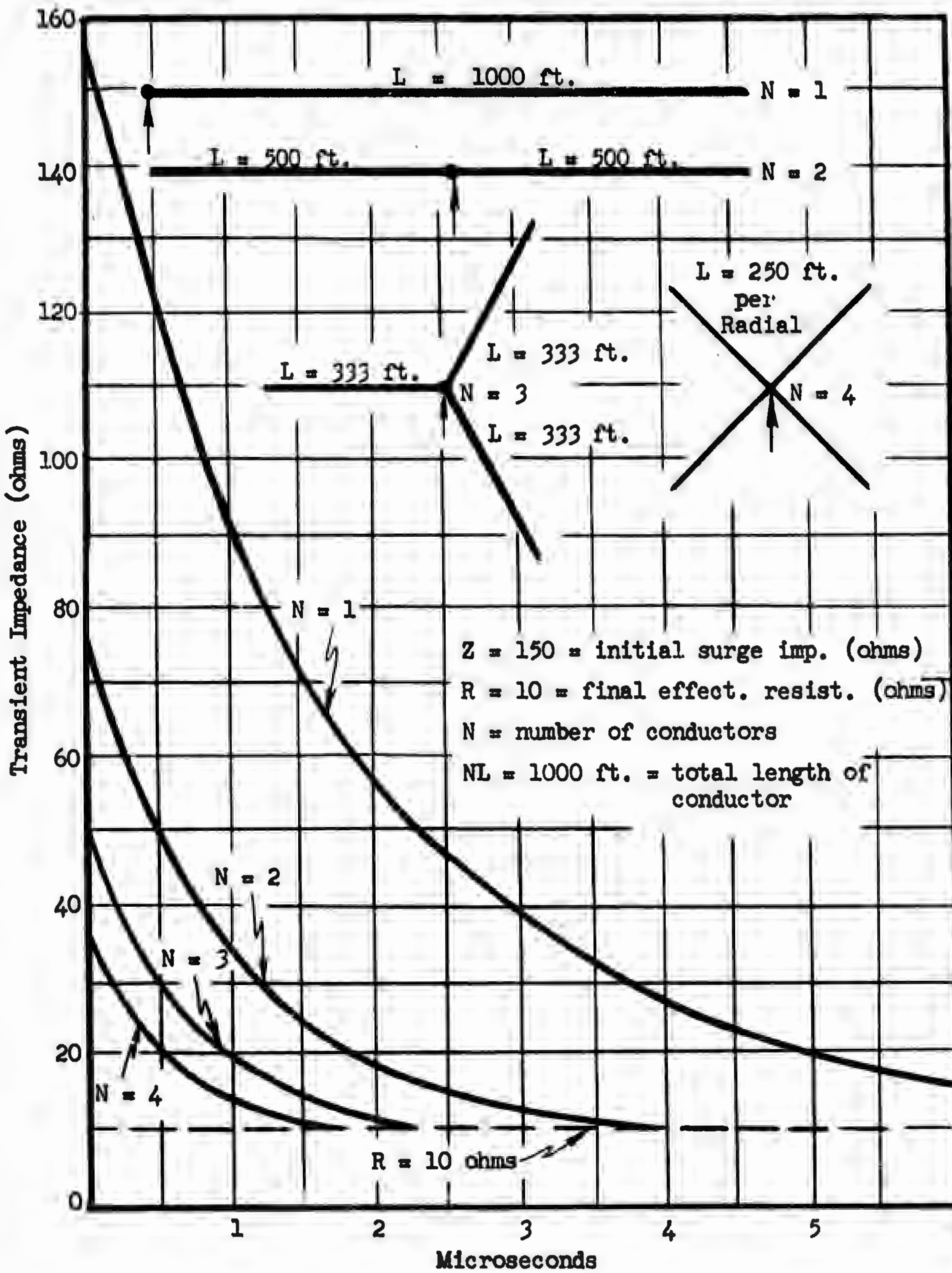


FIGURE 10.7 Transient Impedance of 1000 feet of Counterpoise, as a Function of Number of Radial Conductors

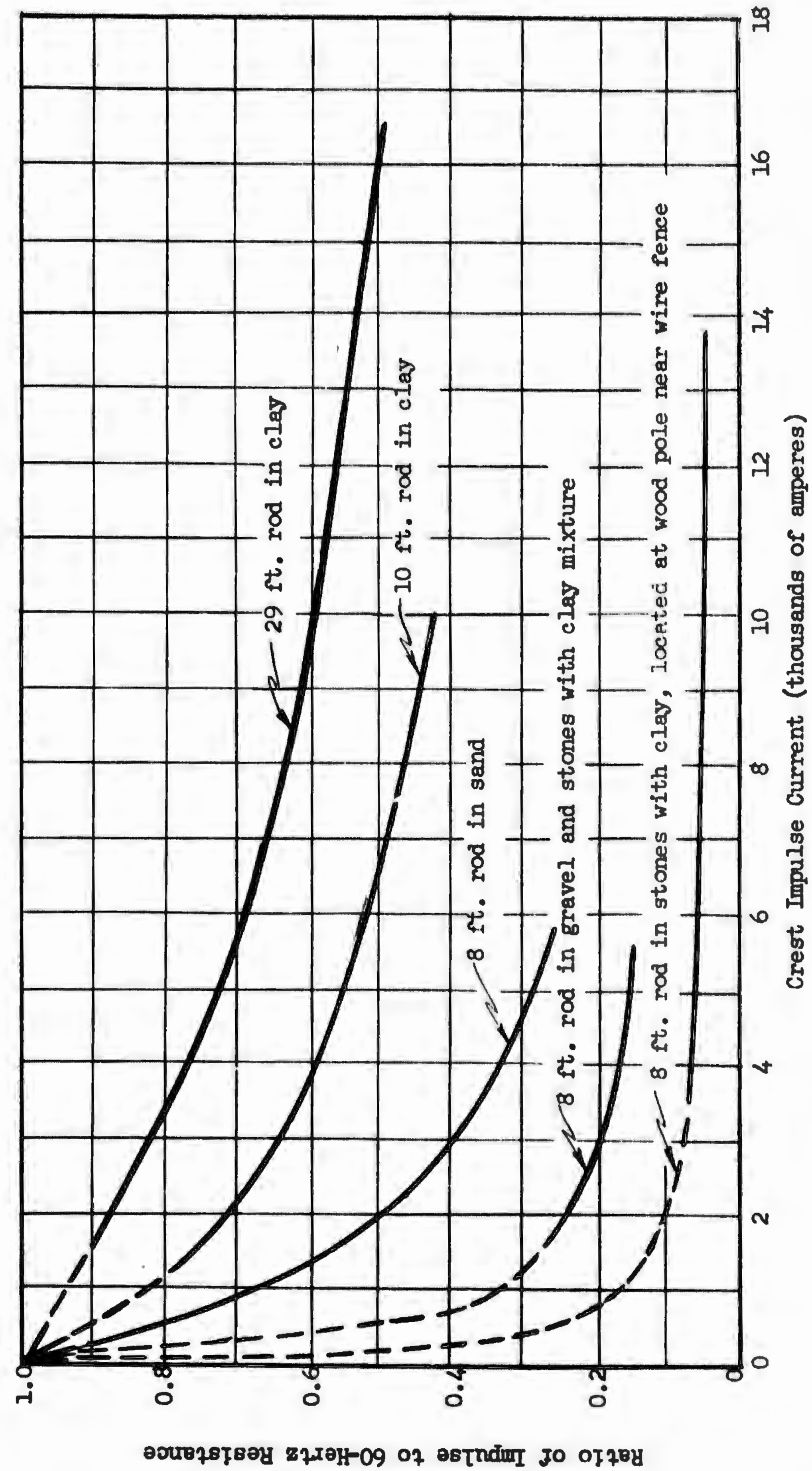


FIGURE 10.8 Resistance of Various Ground Rods to Current Impulses

electrical connections of conduits or piping to structural metal, or interconnection of reinforcing metals in concrete structures. Bonding is necessary for the following reasons:

1. Bonding provides a minimum resistance and direct path for surge current from the point of entrance to the earth.
2. Bonding protects personnel from shock hazard, resulting from internally faulted equipment.
3. Bonding prevents the accumulation of static charges that produce radio interference as well as create a shock hazard and, by periodic sparking, an explosion hazard.

Applications of bonding usually involve flexible connections, capable of withstanding vibration and shock. Materials used for bonding should be able to resist fatigue; substitutions of improper, shorter, or fewer bond straps than recommended can compromise safety. It is essential that bonds be inspected at regular maintenance intervals and replaced promptly whenever broken strands are discovered.

Bonding application in connection with shielding and the other protection techniques is fully covered in Section 5.0.

10.2 Cathodic Protection of Grounding Systems

10.2.1 Concept of Galvanic Action

For the protection of personnel and electrical equipment, power plants and similar installations are constructed with an extensive grounding grid, bonded to other metal structures to provide low resistance return paths for fault currents. This protective network generally consists of various metals selected for reasons other than their resistance to corrosion. When buried in conductive soil, these dissimilar, interconnected metals constitute a large galvanic cell, as shown in Figure 10.9, which can produce corrosion of underground structures.

A galvanic cell is created when relatively uncorrodible metals, such as copper, are buried in low resistivity soil in close proximity to more

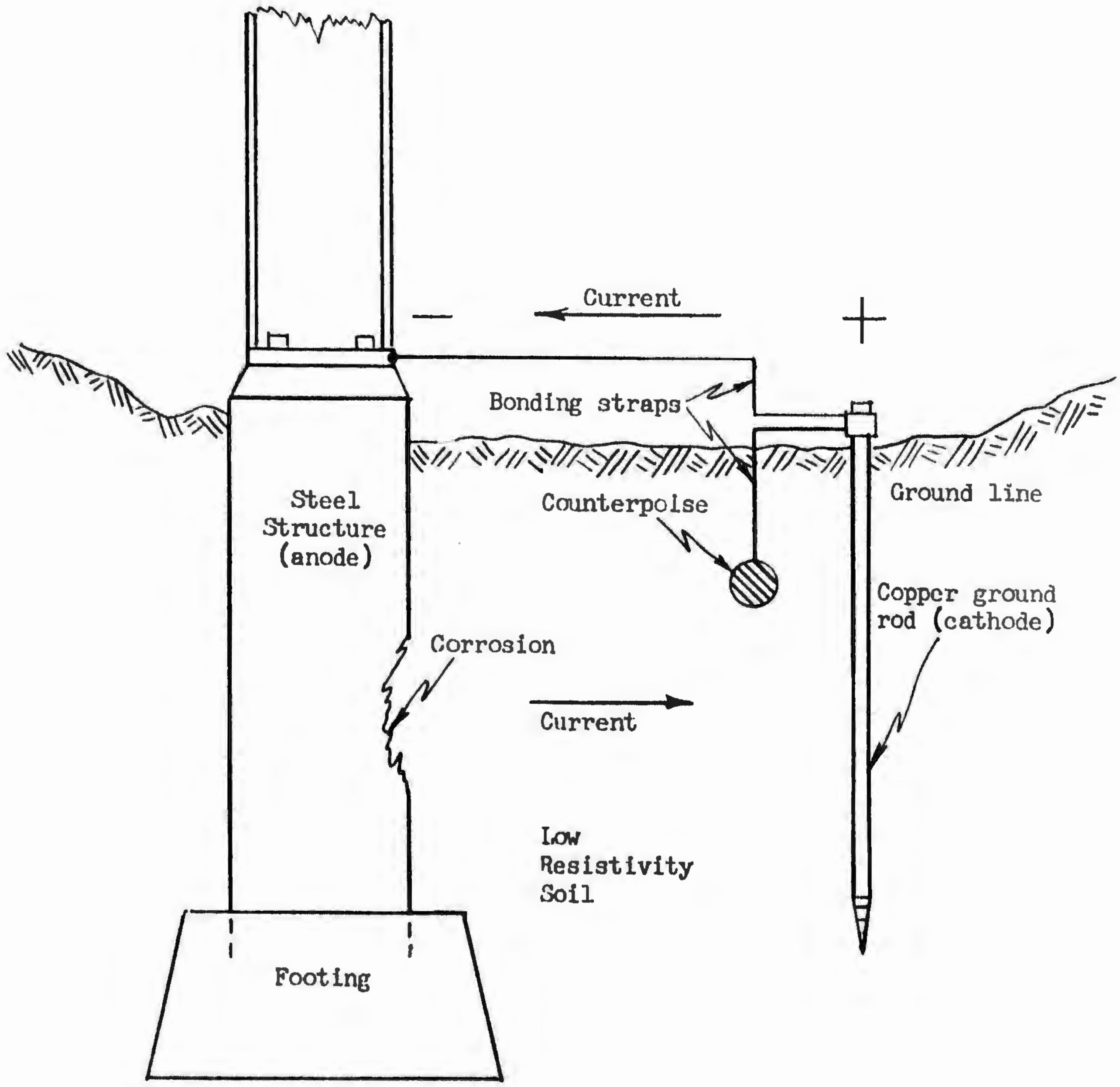


FIGURE 10.9 Galvanic Cell Created by Dissimilar Metals Interconnected and Buried in Conductive Soil

corrodible metals, such as steel. Such soil, acting as an electrolyte, completes the circuit. The degree of galvanic action that results is influenced, in part, by the relative positions of the metals in the Electromotive Series, as shown in Table 10.4.

Potentials of the metals in the Electromotive Series are expressed with reference to the arbitrarily designated zero potential of the normal hydrogen electrode. The present convention is to show alkali metals as negative; thus an ordinary dc voltmeter must have its positive terminal connected to the cathode, or noble, terminal of a galvanic cell and its negative terminal connected to the anode, or corrosive, terminal of the cell to read upscale. In Figure 10.9 the steel is the negative terminal and the copper is the positive terminal.

It is important to note that this table should never be used as more than a rough guide to the behavior of a galvanic couple, because the potentials are profoundly influenced by the films formed on the surfaces of the metals. These films, in turn, depend on the chemical composition of the electrolyte and other environmental factors.[13]

The amount of corrosion current is governed by the relative potentials of the dissimilar metals and by the resistivity and temperature of the soil. Consequently, the higher the differential between the metal potentials and soil temperature and the lower the soil resistivity, the greater the rate of galvanic corrosion. The corrosion rate is also affected in a degree by the distance between the anode and cathode metals and their area ratio.

Structures found to be particularly vulnerable to corrosion are generally those placed close to electrical grounds. These include the following:

1. underground metallic pipes such as gas, oil and water lines, sewer pipes, drains, and culverts.
2. tower footings for electrical transmission lines.
3. pole line ground anchors and rods.
4. tower footings for radio transmitters.

TABLE 10.4

ELECTROMOTIVE SERIES OF METALS[13]

Based on Hydrogen Reference Electrode = 0.00 V

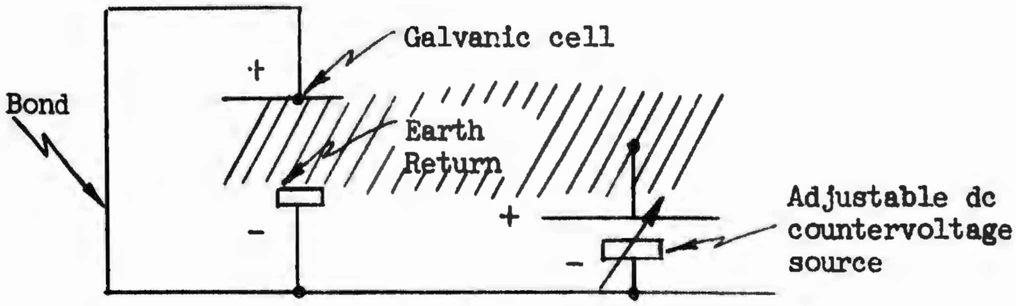
Metal	Potential in Volts	
Sodium	- 2.71	↑
Magnesium	- 2.37	
Zinc	- 1.10	
Aluminum Alloys	- 0.93 to - 0.70	Alkali or
Cadmium	- 0.80	Anodic End
Steel Alloys	- 0.51 to - 0.43	(Corrosive)
Wrought or Cast Iron	- 0.42	
Lead	- 0.40 to - 0.12	
Tin	- 0.39 to - 0.13	
Brasses	- 0.05 to - 0.07	
Tungsten	+ 0.05	
Antimony	+ 0.10	
Copper	+ 0.25	
Bronzes	+ 0.25 to + 0.27	
Cupro-Nickel Alloys	+ 0.28 to + 0.30	Noble or
Monel	+ 0.31 to + 0.33	Cathodic End
Nickel (passive)	+ 0.35 to + 0.38	(Non-corrosive)
Stainless Steels (passive)	+ 0.57 to + 0.64	
Mercury	+ 0.79	
Silver	+ 0.80	↓

5. buried and on-ground storage tanks.
6. circulating water intake screens and frames.
7. water boxes of surface condensers and heat exchangers.
8. exterior and interior surfaces of storage tanks.
9. building steel-reinforcing mats.

10.2.2 Approaches to Cathodic Protection

Cathodic protection, or measures for lessening the effects of galvanic action, can be provided by three general methods. These are often used in combination and are as follows:

1. Coating. All ungrounded metallic surfaces except those left bare for grounding purposes are carefully coated with a material having suitable electrical insulation strength and chemical ability to resist corrosion damage over a long period.
2. Sacrificial Anodes. These anodes, often used in conjunction with protective coatings, are electrically connected to the metal structure, pipe, etc. that requires protection. Sacrificial anodes are composed of an alkali metal having a highly negative electromotive potential to act as the anode of a galvanic cell. Thus, current from the structure tends to travel through this anode corroding it rather than attacking possible bare areas in the protective coating. These anodes are often installed in water tanks and intakes to react with corrosive water and protect the metal interiors. Because of their function as corroding anodes, they are expendable; therefore, they must be inspected at regular intervals and replaced periodically.
3. Opposing Voltage. This technique of cathodic protection utilizes an outside source of voltage opposing the voltage of the galvanic cell. As shown by Figure 10.10, this countervoltage source is installed with its negative terminal connected to the structure being protected and its positive terminal connected to a remote drain



Schematic

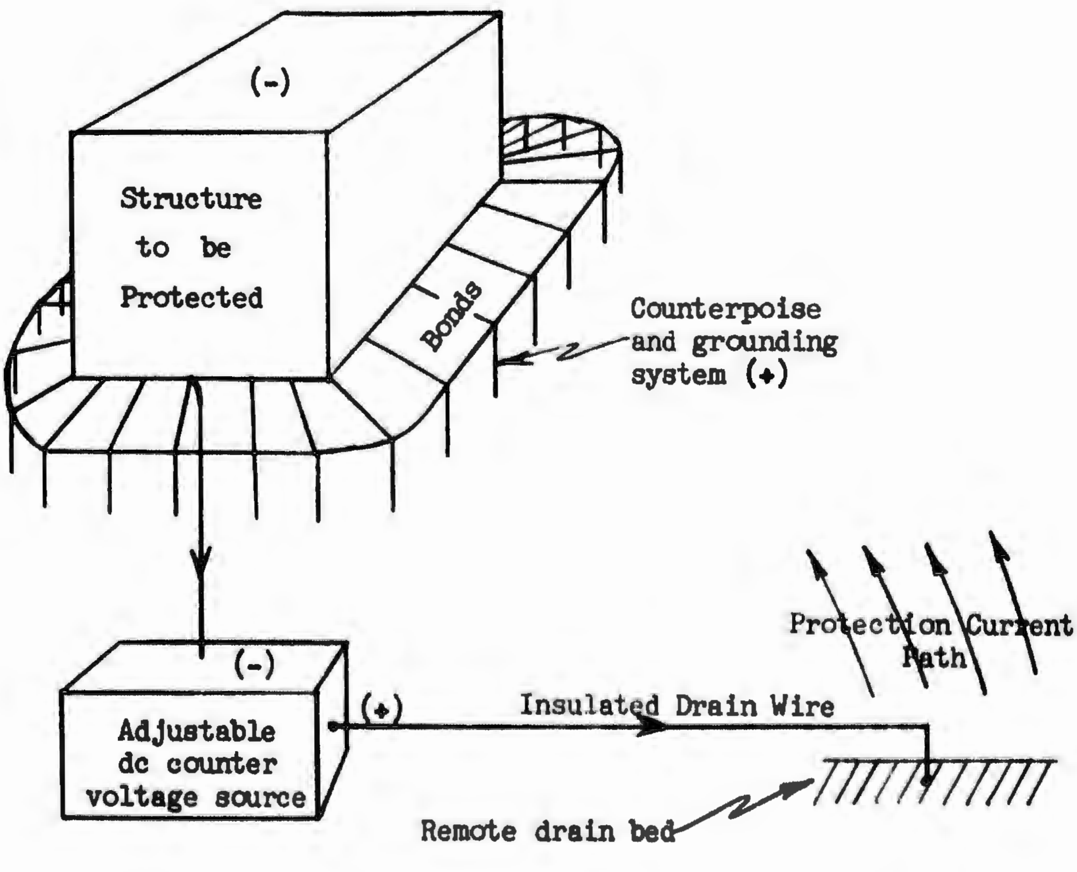


FIGURE 10.10 Connections for Cathodic Protection Utilizing the Opposition Voltage Technique

bed. By adjusting the opposing power source, the galvanic potential of the building or elements to be protected can be offset, minimizing the galvanic current and its corrosive effects.

In water tanks and water intakes, anodes connected to the positive side of a dc power source will provide the required protective current. Such anodes require periodic changing.

Combinations of all three of the above cathodic protection methods are used in most large installations. The extent to which these are applied depends entirely upon the corrosive environment. Coatings should not be used as the only means of cathodic protection because corrosion effects will then be concentrated at all the weak points in the coating. Sacrificial anodes and/or an electrical cathodic system are also required to minimize these effects.

10.2.3 Cathodic Protection of Electrical Installations

Cathodic protection of extensive electrical installations such as a power plant and its interconnected remote facilities will involve making a preliminary survey to determine incidence of the site to corrosion, correlation of this preliminary survey with the plant layout, applying cathodic protection techniques, and conducting certain measurements after the construction is complete. Each of these steps will be covered in detail in the following subsections.

10.2.3.1 Preliminary Survey

The requirements for cathodic protection of a power plant or similar installation require an initial survey of the environmental conditions at the site. The survey should include climatic temperature, drainage and aeration, soil resistivity, "half cell" potential measurements, and corrosion data history on other or previous installations in the vicinity.[14] Details of each of these survey factors are given below.

1. Temperature. Corrosion takes place when the anode of a galvanic cell disintegrates in an aqueous solution (electrolyte). The

electrochemical reactions are influenced exponentially by temperature; discontinuities occur at or below freezing levels.

2. Drainage and Aeration. Drainage and aeration affect the chemical action and resistivity of the soil. In areas that are poorly drained (in effect, submerged), chemical impurities may increase the electrical conductivity of the electrolyte and accelerate the rate of corrosion.

3. Soil Resistivity. Soil resistance measurements should be made at the site and plotted on a map of the proposed installation. When appraising resistivity measurements of the soil in a given area, maximum resistivities should be disregarded, because these can be due to local inclusions of rock, gravel, or sand, or to a local condition of high surface resistance. Resistivity varies with the type of soil and may range from practically zero to 3000 or more ohms-meter. Table 10.5 lists average resistivities for various kinds of soil.

TABLE 10.5

TYPES OF SOIL AND RESISTIVITIES[21]

Soil	Resistivity (ohms-meter)
Sea Water	Practically zero to 0.35
Fly Ash, Cinders	2 to 20
Red Clay	15 to 50
Yellow Clay	50 to 150
Loam	50 to 300
Sand, Gravel	150 or more

Wide variations in soil resistivity are often found in areas only a few miles apart. It is possible that at a given site the resistivity variations may be small, but in extreme cases, they may be quite large. The actual locations of areas with different

soil resistivities should be known in order to provide adequate cathodic protection. In soils with resistivities greater than 100 ohms-meter, the threat of corrosion is not enough to cause concern. Soils with resistivities less than 100 ohms-meter are the ones that can cause corrosion. The degree of corrosion can be classified as shown in Table 10.6.

TABLE 10.6

CORROSION AS A FUNCTION OF SOIL RESISTIVITY[14]

Soil Resistivity (ohms-meter)	Corrosion Effect
10 or less	Severe
10 to 50	Mild to Severe
50 to 100	Mild, if aerated
100 or more	Very mild

4. "Half Cell" Potential Measurements. At the site where soil resistance measurements are made, measurements should also be taken of the potential between structural steel elements and a copper/copper sulfate "half cell" (see Section 10.2.5). Such potential measurements are needed particularly in those areas where resistivity readings were low and buried structures are to be located. These potential readings afford a second method of checking possible corrosive action and they are related to corrosion as shown in Table 10.7.

TABLE 10.7

CORROSION AS A FUNCTION OF POTENTIAL BETWEEN METALS TAKEN WITH $Cu/CuSO_4$ "HALF CELL"[14]

Volts Steel to Copper (minimum)	Probable Corrosion Effect
0.55 or more	Severe
0.45 to 0.55	Moderate
0.30 to 0.45	Mild
0.15 to 0.30	Very mild
0.15 or less	Practically none

5. Corrosion History. If any reasonably complete corrosion information for the area is available, it can usually be obtained from local utility companies. This history should not be used as design information, but it is useful to correlate with the results of the resistivity and potential measurements taken at the site.

10.2.3.2 Correlation of Preliminary Survey and Plant Layout

A layout should be made of the proposed plant site. All plant components such as building, tunnels, pipes, tanks, fences and grounds should be indicated. Although complete details may not be available, information as to types of material and the general location of dissimilar metals can be estimated. This layout, correlated with the results of the corrosion survey, will fairly well define the system cathodic protection requirements.

10.2.3.3 General Practices for Cathodic Protection

This section lists briefly the general practices for applying cathodic protection; specific practices are given in Section 10.2.4.

1. Concrete provides an excellent protective coating for steel, copper, and zinc and is used on all structures wherever possible. Steel encased in concrete assumes a more cathodic or noble potential than steel in direct contact with soil. The potential developed by steel in concrete is usually of the same polarity and order of magnitude as copper in soil. Therefore, very little corrosion will circulate.
2. Other coatings are used for all metals such as pipes and tanks that cannot be encased in concrete. Such coatings are composed of different grades of coal-tar and asphalt enamels with various reinforcements added. The principal value of coating is to interpose electrical resistance between the electrolyte and the metal and to keep the metal dry in order to inhibit corrosion.
3. Sacrificial anodes, as previously described, are used in conjunction with surface coatings, especially in those areas where the

coating may be inadequate or where no coating can be applied because of mechanical problems.

4. Electrical cathodic protection systems employing externally energized anodes are used wherever coatings and sacrificial anodes are not capable of minimizing the corrosion current. Provisions should be made in the plant design for installation of these systems if initial design indicates a marginal condition with regard to corrosion severity. Attachment of metal coupons to structures or burying metal samples in suspected areas of severe corrosion may aid in identifying the need for an electrical cathodic protection system. More than one such system may be required for a site, depending upon the distance between buildings, the lengths of water intakes and pipe runs, etc.

10.2.3.4 Post-Construction Procedures

After the plant is constructed, measurements should be taken of the potential of various structures to a copper/copper sulfate "half cell". Such measurements will indicate the corrosion threat and may dictate the necessity of installing an electrical cathodic protection system. If this type of system has already been installed, the measurements will facilitate adjustment of the system to the proper counter-current levels.

Following construction, all cathodic protection installations shall require periodic checks. These will include inspection of coatings, "half cell" potential measurements, adjustment of electrical cathodic protection system(s), or replacing sacrificial anodes.

10.2.4 Specific Practices in Cathodic Protection

Specific practices to be followed when applying cathodic protection are detailed in the next eight subsections.

10.2.4.1 "Half Cell" Potential Criteria

All cathodic protection systems are designed basically to provide alkali or corrodible metals such as steel with a negative potential greater

than the potential of copper, as referenced to a copper/copper sulfate "half cell".

Table 10.8 lists metals and typical potentials normally observed in neutral soils and waters, measured with respect to this $Cu/CuSO_4$ "half cell".

TABLE 10.8

TYPICAL POTENTIALS OF METALS NORMALLY OBSERVED IN NEUTRAL SOILS AND WATERS[16]

(referenced to a copper sulfate electrode)

Metals	"Half Cell" Potentials
Commercially pure magnesium	- 1.75 V
Magnesium alloy (6% Al, 3% Zn, 0.15% Mn)	- 1.6 V
Zinc	- 1.1 V
Aluminum alloy (5% Zn)	- 1.0 V
Commercially pure aluminum	- 0.8 V
Mild steel (clean and shiny)	- 0.5 to - 0.8 V
Mild steel (rusted)	- 0.2 to - 0.5 V
Cast iron (not graphitized)	- 0.5 V
Lead	- 0.5 V
Mild steel encased in concrete	- 0.2 V
Copper, Brass, Bronze	- 0.2 V
High-silicon cast iron	- 0.2 V
Mill scale on steel	- 0.2 V
Carbon, Graphite, Coke	+ 0.3 V

These values of potentials are normally observed in soils and waters which are neither markedly acid nor alkaline. Depending on actual conditions, individual potential measurements may vary by 0.2 volt or more.

All measurements shall be made using a copper/copper sulfate "half cell" with a potential of 0.3 volt as the reference anode. To exceed the steel to copper potential requires that the steel, when measured with the copper/copper sulfate "half cell", be greater than - 0.85 volt. (Normal

practice is to maintain a potential from - 0.85 volt to -1.00 volt by using some form of cathodic protection.)

10.2.4.2 Concrete Coating

The following criteria will apply to concrete coatings:

1. All underground metal structures, except piping and cabling and rods used for grounding purposes, should be encased in at least two inches of concrete. The concrete mixture, unless specified for construction purposes, shall be composed of one part Portland cement and two or three parts of coarse, washed sand. Calcium chloride or other salts used as concrete additives should be eliminated or restricted to contents of less than one percent.
2. Metallic piping (conduits, etc.) shall be coated with insulating organic materials as prescribed in Section 10.2.4.3, but in addition, concrete coatings not less than two inches thick shall be applied over such piping for a distance of twenty feet from any structure. At all junctions of the concrete and organic coatings, the organic coating shall be applied first, followed by the concrete coating extended over the insulating coating for at least two feet. Care must be taken to avoid uncoated metal in the piping or conduit runs, because steel encased in concrete tends to be highly cathodic to bare steel; exposed sections will be subject to severe galvanic corrosion.

10.2.4.3 Other Coatings[14]

On all metallic pipelines, conduits, etc. beyond the immediate vicinity of the main power plant foundation, various insulating type coatings may be used. There are three basic types: coal-tar enamel, asphalt enamel, and plastic tapes. The selection of a coating system depends to an appreciable extent upon the type of soil encountered.

Primers shall be applied to the cleaned pipe to ensure a tight bond between the metal and the enamel. These primers are sticky, with good wetting characteristics. They adhere readily to the metal and provide an

organic surface to which the hot coal-tar or asphalt enamel can bond. Preparation for the primer coat requires sandblasting, especially at weldments, in good, dry weather when the pipe is warm. The primer shall be applied and the pipe coated with enamel before the primer collects dirt. Then shall normally follow a coating reinforcement of woven asbestos, either treated or untreated; this latter application is to protect the enamel by resisting displacing forces of stones and other abrasive bodies.

Enamel coatings are furnished in narrow, moderate, and wide ranges. The term "narrow range" refers to the limited temperature range through which such an enamel may be used. For example, a narrow-range enamel that softens at 90°F will flow and sag on a vertical surface above 110°F and will crack and disbond if subjected to temperatures below 30°F. The range of 110°F - 30°F, or 80°F, is referred to as "narrow". Moderate-range enamels are stable over a range from 0°F to 140°F, while wide-range enamels can be used from -20°F to 160°F.

Pipeline tapes are made of plastics such as polyethylene, polyvinyl chloride, and polyvinylidene chloride, coated with sticky adhesives of rubber-resin mixtures. These "long chain" polymers are free from cold-flow, chemically inert, and resistant to organisms. They are comparatively resistant to pressure, but can be cut by sharp edges of stones.

Resistances of new enamel coatings can range from a few thousand to several million ohms per square foot. Old coatings can deteriorate to less than 100 ohms per square foot, but may retain a very high resistance if they are of exceptional quality. Plastic tapes have resistances of 20,000 to 300,000 ohms per square foot. Because of their chemical stability, plastic tapes can maintain this value of resistance in service.

There is no complete agreement among authorities as to exactly what is the most economical procedure for coating and evaluating coatings except on one point; no coating is perfect. It is almost universally agreed that any coating, no matter how carefully applied, will have holes in it after being

subjected to soil pressure and abrasion for an appreciable length of time. Therefore, if the environment is corrosive, coatings alone cannot be depended upon to protect pipes and other underground and underwater structures. Some supplementary form of cathodic protection, is then, an economical way to, in effect, plug the holes in coatings. If cathodic protection is applied, the cost is not greatly increased by a relatively large increase in the number of discontinuities, or "holidays", in the coating.

"If the environment is not corrosive, neither coating nor cathodic protection can be justified economically; but if one is justified, the other is also, inasmuch as a combination of the two is more economical than cathodic protection alone. Finally, cathodic protection costs little, if any, more for pipes and structures with fair, inexpensive coatings than for superior, expensive coatings. This does not imply that a coating of poor material or workmanship is justified. The coating should be of high strength and high resistance, properly applied on a well-prepared surface, but without extras."[14]

10.2.4.4 Sacrificial Anodes

Magnesium and zinc are the two metals most commonly used for sacrificial anodes. The dissolution rate of magnesium anodes can be estimated at from 300 to 500 ampere-hours per pound. Such anodes are normally obtained with a rating indicating current, life, and weight. For example, a 17-pound anode would be rated at 0.08 ampere (80 milliamperes) for ten years. Anode life would be approximately in inverse proportion to current load, as shown in Table 10.9.

Magnesium anodes are buried in the ground, surrounded with backfills generally composed of bentonite and gypsum. Surface current densities range from 33 to 200 milliamperes per square foot. The potential of these anodes to a copper/copper sulfate "half cell" would measure about - 1.6 volts.

TABLE 10.9

ESTIMATED LIFE OF 17-POUND MAGNESIUM ANODE AS A FUNCTION OF CURRENT[14]

Estimated Life (years)	Anode Current (amperes)
10	0.08
8.3	0.12
4.5	0.24
2.5	0.47

The dissolution rate of zinc anodes can be estimated as 335 ampere-hours per second. The life of these anodes is not influenced by surface current density, and zinc anodes can be designed for long life. These anodes are also installed in backfills of bentonite and hydrated gypsum. Their potential to a copper/copper sulfate "half cell" is about - 1.1 volts.

The choices of shape and size of magnesium or zinc anodes depend on the current requirements and also on soil resistivity and desired length of anode life. In selecting a magnesium anode shape and size, the anode area should be large enough to conduct the required current, but yet as small as practicable to be favorable to the ampere-hour output per pound of magnesium. In very low resistivity soil, or in sea water, the lower output voltage of zinc at a relatively low price per pound is preferable to the high output voltage of magnesium at a higher price per pound. In soils of somewhat higher resistivities, the higher output voltage of magnesium is advantageous. Both zinc and magnesium anodes are primarily restricted to installations where cathodic current requirements are small, and where the environment has relatively low resistivity. If larger cathodic protection currents and higher output potentials are needed, an electrical cathodic system should be used.

10.2.4.5 Electrical Cathodic Systems

Rectifiers operated from reduced ac inputs are commonly used as the source of dc power for electrical cathodic systems. Because of their larger current and higher voltage capability compared with sacrificial anodes, they are used for the protection of extensive underground metallic masses such as large pipe lines. The rectifiers are frequently hermetically-sealed, oil-immersed units, especially in outdoor installations; however, the transformers are usually dry-type.

Remote ground beds of the electrical cathodic protection system consist of either graphite or high-silicon cast iron anodes in a coke-breeze or carbonaceous backfill. Either vertical or horizontal anode configurations can be employed; the choice is dependent on variations of soil resistivity with burial depth. Open-hole, deep-well ground beds are desirable where geologic conditions permit their construction. In unconsolidated formations that can be held open with drill mud, economical deep-well ground beds can be constructed by installing anode canisters. However, horizontal ground beds usually will be the conventional type of installation, with the anodes located near the surface in a straight line configuration.

10.2.4.6 The Current Density Requirements for Cathodic Protection

Soil or water corrosivity at a site is the principal factor dictating the need of cathodic protection for buried or immersed steel structures.

Tests[15] with bare steel having direct contact with very corrosive soil indicate that cathodic protection current densities ranging from 5 to 25 milliamperes per square foot are required to inhibit corrosion. By comparison, a current density of 3 milliamperes per square foot can virtually eliminate corrosion of sheet piling below mean low tide in sea water, while 2 milliamperes per square foot can protect bare steel submerged in a relatively quiet river above tidewater.

When the steel is coated, as outlined in Sections 10.2.4.2 and 10.2.4.3,

the current density requirements for cathodic protection are very much less than those for bare metal. As examples, well-coated pipelines may require only 0.01 to 0.02 milliamperes per square foot in soils with resistivities from 6 to 40 ohms-meter. An important pipeline in this country is being protected by current averaging 0.0025 milliamperes per square foot. Current densities can be expected to increase with age and as soil damage develops discontinuities in coatings.

In practice, periodic checks are made of the current circulated by electrical cathodic protection systems, which are usually operated in conjunction with coatings on the structures. Any radical increases in cathodic current are indicative of coating deterioration.

10.2.4.7 Examples of Cathodic Protection for Equipment

1. Intake Screens

Intake screens, where cooling water is taken from a river, lake, or ocean, will require cathodic protection. Either electrical cathodic systems or sacrificial anodes can be used. If galvanic anodes are considered, the chemical composition of the water flowing through such intakes must be taken into account to verify that there are no constituents in the water that may cause an anode to be passive.

Zinc anodes 2 inches by 2 inches by 60 inches are often welded directly to the steel side bars of intake screens. The life of the anodes will vary with the resistivity of the water and will also depend upon the kind of material used for the screen cloth. In sea water, where screen cloth of copper alloy is used, anodes may have to be replaced annually; in higher resistivity water, life expectancy is longer. The actual size and type of anode will depend on water conductivity, life desired, and current requirements.[17]

When cathodic current requirements are high, rectifier systems should be specified. It is necessary that the cathodic protection electrodes be properly located within the intake chamber, so that the

cathodic current will be reasonably well distributed throughout the structures being protected. For this particular application, these electrodes are connected to the positive side of the rectifier and the negative side of the rectifier goes to a remote ground bed.

2. Tank Interiors

Tank interiors can be protected either by zinc or magnesium anodes or by an electric cathodic system. Sacrificial anodes are commonly used in conjunction with insulated coatings. With either type of system, however, electrodes need to be distributed in a manner tailored to the tank design.

3. Condenser Water Boxes[18]

Condenser water boxes can be protected from corrosive effects by one of the following methods:

a. Non-aggressive waters - apply insulating coatings to materials that are cathodic to the steel or cast-iron box.
b. Non-aggressive waters - apply insulating coatings to sheet and tube ends and apply a zinc-rich coating to water box interior surfaces.
c. Non-aggressive waters - apply a mesh-reinforced coating of Gunite to the ferrous water box surfaces.
d. Aggressive waters - use the coatings described in Item b. above, plus distributed sacrificial anodes.
e. Aggressive waters - use the coatings described in Item b. above, plus an electrical cathodic system with distributed electrodes.

10.2.4.8 Other Cathodic Protection Considerations

1. Sheet Steel Piling and Reinforced Concrete Piling

Steel sheet piling in sea water will require protection either from zinc anodes or by use of an electrical cathodic protection system. Reinforced concrete piling will not be inherently

protected by the concrete coating, since the movement of sea water forces salt between particles of concrete. This kind of piling is usually protected by an electrical cathodic system and it is essential that electrically conductive bonds be used between individual piles.

2. Copper Ground Cable

Bare copper ground cable shall not be used in direct burial applications except where required for counterpoise and counterpoise connectors. In all other applications, copper cables should be insulated with neoprene jackets. Special cathodic protection cable (coated with 7/64 inch polyvinylchloride jacket) are recommended for the electrical cathodic system.

Bare copper ground cable shall not be installed in steel conduit, but for construction purposes can be run through fibre duct or flexible plastic conduit. All underground splices and connections should be taped and suitably waterproofed.

3. Welding Equipment

During the construction of a power plant or industrial plant, considerable corrosion damage to buried structures can result from the improper grounding of welding equipment. To avoid this, electric welding equipment shall always be connected electrically to the particular structure being welded.

10.2.5 Cathodic Protection Measurement Techniques

The preliminary survey of system cathodic protection outlined in Section 10.2.3.1 will require specific knowledge of soil resistivity at the site and enough "half cell" potential measurements to predict corrosion severity. After construction, determinations should be made of the resistance of conduit, pipeline, tank, and other accessible structure coatings, and potential test measurements should be made to insure that a cathodic protection system, if required, is properly adjusted. This section

outlines the techniques for making these measurements.

1. Soil Resistivity Measurements

   Resistivity measurements in undisturbed soil are usually made with a soil resistivity meter by the Wenner "four-pin" method illustrated in Figure 10.11. This method uses four pins set up in alignment on grade. The two outside, or current, electrodes (C1 and C2) are 3D meters apart and the two inside, or potential, electrodes (P1 and P2) are D meters apart. This, in principle, is a "fall-of-potential" method with the resulting resistance (R) between pins indicated on the instrument scale. Average soil resistivity, ρ in ohms-meter, at a depth below grade corresponding to the distance D between potential pins P1 and P2 is then

$$\rho = 2\pi DR \qquad (12)$$

2. Cathodic Protection Potential Measurements

   The voltages developed by galvanic action between buried or submerged steel structures and other metals cathodic to steel are generally not measured directly, but by the use of "half cells"; the copper/copper sulfate "half cell" is the most common for field work. The remaining "half cell" of the galvanic couple consists of the iron in the steel together with the soil or other aqueous environment. These two together produce a potential difference as in any other complete cell. The main advantage of this arrangement is that the copper/copper sulfate "half cell" can be moved readily from one position on the iron/soil "half cell" to another for measuring potential difference between the iron and the soil electrolyte at different points in the electrolyte.

   Commercial "half cells" consist of a plastic tube with a porous wooden plug in one end and a copper rod supported by a plastic or metal closure at the other end. Copper sulfate in a saturated aqueous solution is used as the electrolyte. Details are shown in Figure 10.12.

T_1 and T_2 are current source.

T_3 and T_4 are potential terminals.

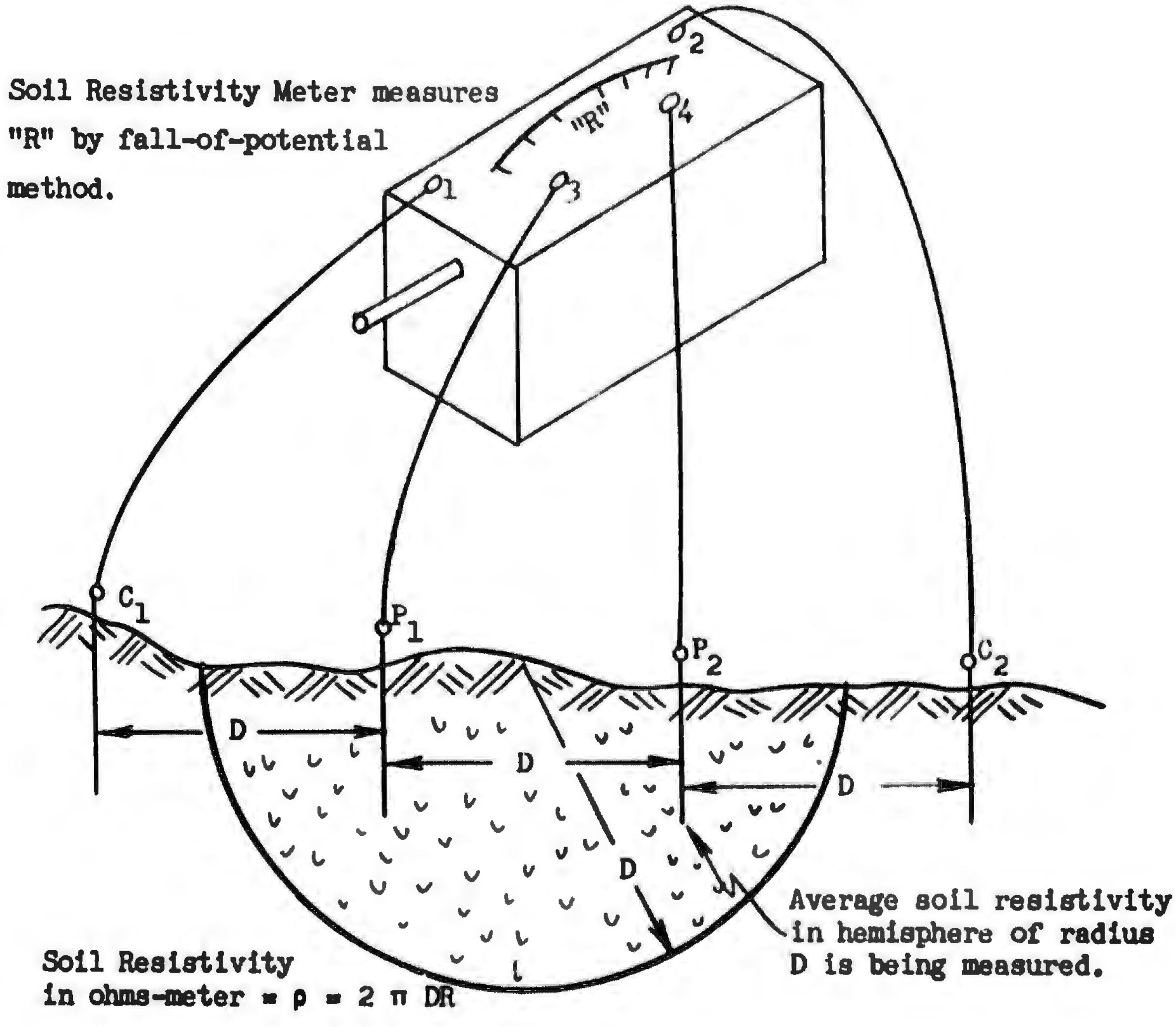


FIGURE 10.11 Four-Electrode Method of Soil Resistivity Measurement

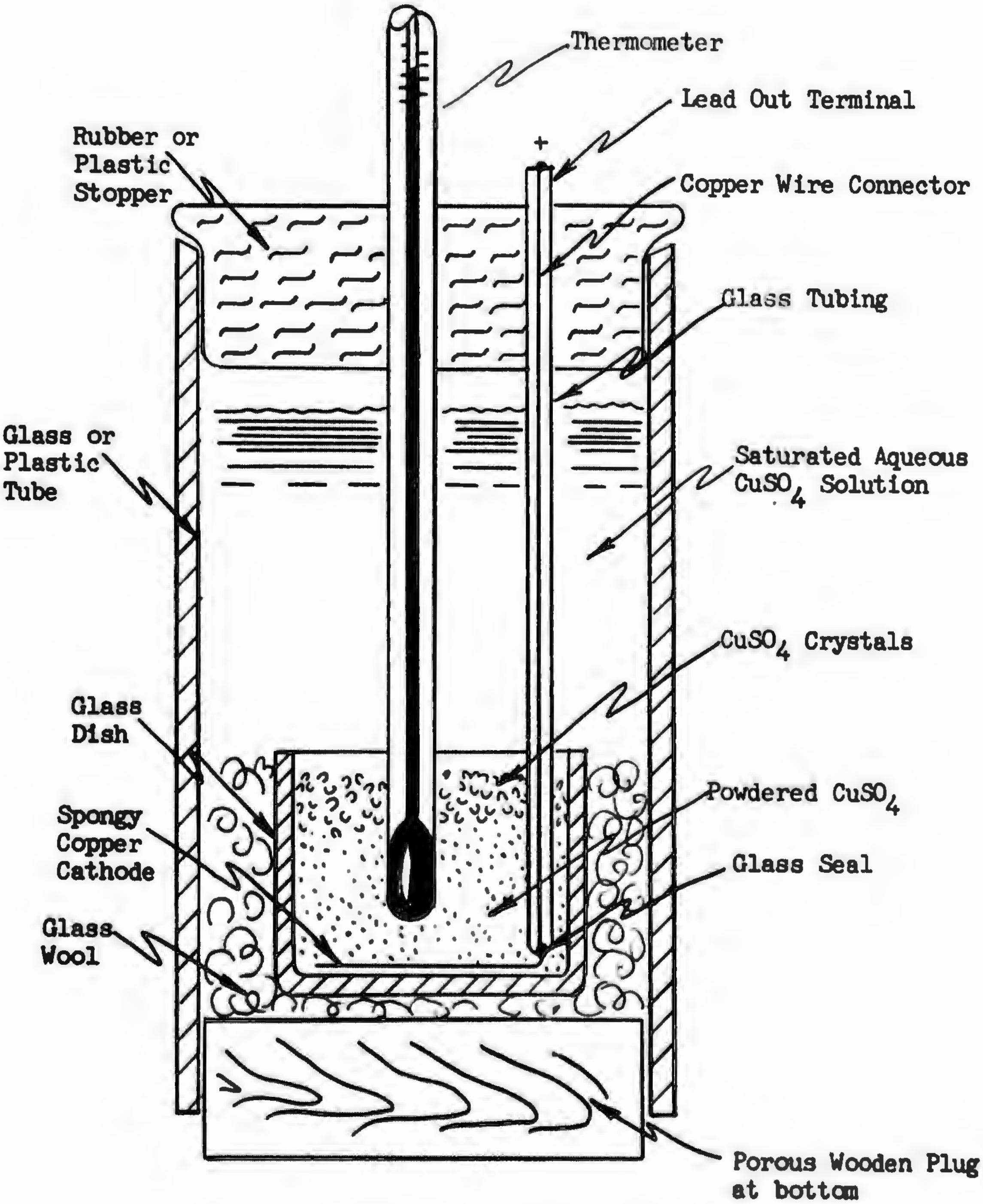


FIGURE 10.12 Construction Details of Copper/Copper Sulfate Half-Cell

Since only the small potentials (of the order of one volt) developed by the composite galvanic cell indicate the degree of corrosivity, it is very important that accurate measurements be taken. The instrument best suited for potential determination is the potentiometer, because it does not load the galvanic cell. A high quality dc voltmeter could also be used, provided its resistance is 20,000 ohms per volt or higher.

The potential can be determined with practical accuracy by placing the "half cell" in moist earth close to the structure at which a measurement is desired. Typical connections are shown in Figure 10.13. Usually, placement of the "half cell" is not critical, but its location can be extremely important in measuring potentials on structures equipped with cathodic protection where geometrical considerations may cause current shielding of parts of a structure. On tanks and along pipelines, test points or connections to the structure are usually installed to facilitate the measurements.

An example of the measurements and their application follows. It will be assumed that preliminary investigations, conducted as outlined in Section 10.2.3.1 indicate that the site environment is corrosive, that an electrical cathodic protection system is needed, and that access connections to the buried structures have already been installed at selected locations.

Potential measurements using the combined copper/copper sulfate half-cell and the structure/soil half-cell are taken at the test points before any cathodic protection current is applied. These voltages are recorded for reference and comparison with voltages measured at the same test points with the cathodic protection current circulating.[14]

Cathodic protection voltages are measured under two conditions:

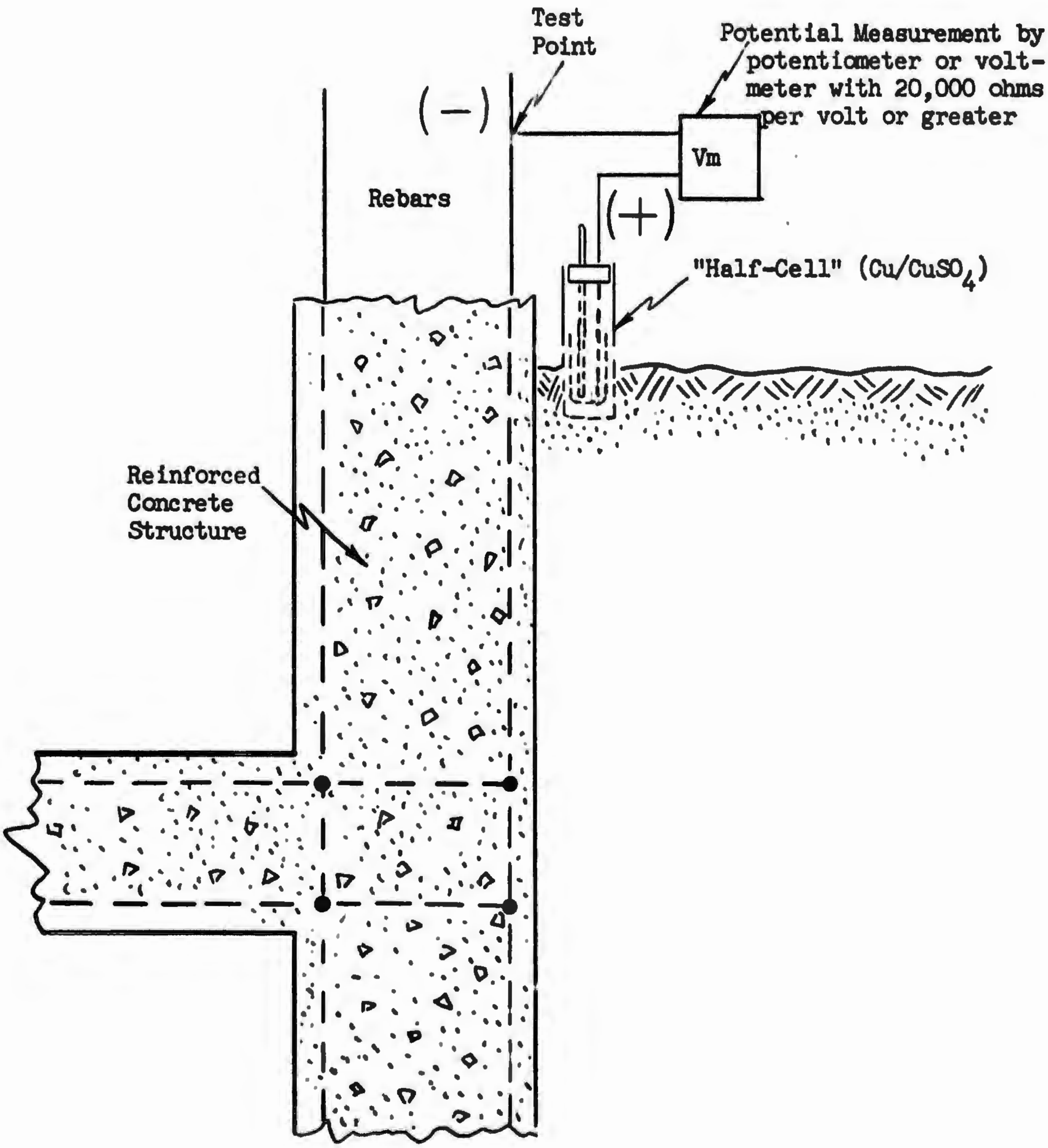


FIGURE 10.13 Cathodic Protection Potential Measurement Setup using "half-cell"

one with the current flowing and the other after the current has been on, but momentarily shut off. The voltage with the current on corresponds to normal operation with cathodic protection. The "momentary-current-off" reading gives an indication of the degree of polarization accomplished while the current was on. Comparison of these voltages will assist an experienced corrosion engineer in estimating the current to be applied for stabilized cathodic protection.[14]

As a criterion for the protection of steel structures, the cathodic current is adjusted until observed protective voltages are at least 0.85 volt, as measured with the copper/copper sulfate half-cell in all parts of the protected area.[14]

The protective current is adjusted until the potential measurements stabilize for a selected constant current. Several hours of operation will provide approximately constant voltages, but these will drift as polarization of the system progresses. Adjustments may extend over many months. After stabilization, the cathodic protection system should be kept in continuous operation.

3. Determination of Coating Resistances

The resistances of most new and some old pipe and tank coatings are sometimes very high. These resistances can be determined by measuring a surface area of several square feet. A current is passed between the pipe and a temporary metal sheath through a layer of moistened paper, measuring the voltage applied. Ohm's Law can then be used as the means of calculating the total resistance of the area of the coating under the sheath. Dividing by the area will give the ohms per unit area and, if the average coating thickness is known, its resistivity can be computed on a volume basis. Details of the test set are shown in Figure 10.14.

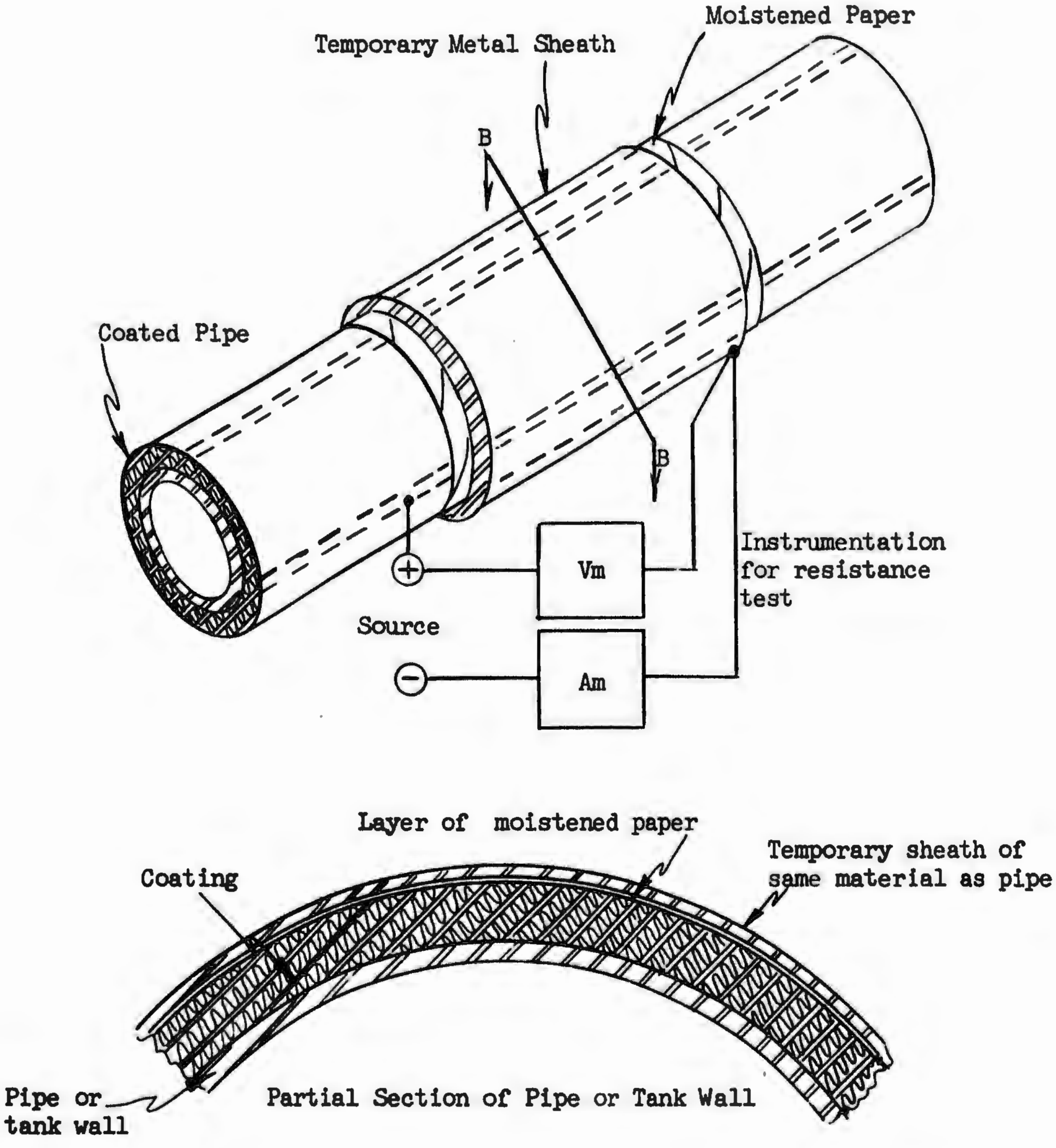


FIGURE 10.14 Method of Checking Resistance of Pipeline or Tank Wall Coatings

10.3 Overvoltage Protective Devices

10.3.1 Introduction and Justification

With increased dependence on electric service by industry and the military, nd the advent of many specialized processes requiring continuity of servic and accurately regulated power, practical methods of controlling surges are important. Surges can originate within localized installations such as the power generating plant due to malfunctioning of fault relaying and synchronizing systems, and in some cases, even from load switching operations. If there is a utility tie, additional sources of surges are introduced. These include sudden load swings, capacitor and other switching operations, and lightning transients. Lightning can produce surges, because the transmission circuits linking an isolated station with a utility system are excellent lightning targets.

When lightning strikes an energized overhead line, it introduces abnormally high voltages on the line while finding the easiest path to ground. In the case of high magnitude and/or long duration surges, the closest line insulators usually are flashed over and, if power current follows the ionized path to ground, a line-to-ground fault occurs.

Sometimes, lightning voltages may be of insufficient magnitude to flash over line insulation and may appear on the line in the form of transient or traveling waves of surge voltage. These waves move away from the stricken point in both directions at approximately the speed of light, stressing the insulation of the lines and all connected equipment. Without surge protection, the insulation of transformers and other terminal apparatus which is usually weaker than the insulation normally provided on lines may be punctured or flashed.

Two basic methods of overcoming the effects of lightning on exposed equipment have been found to be practical:

1. The use of overhead ground wires, which shield energized circuits by intercepting direct lightning strokes. To be effective, such

shielding wires must be properly placed above the power conductors and be adequately grounded.

2. Evaluating the impulse or surge strengths of the line and apparatus insulation and applying suitable shunting devices of lower surge strength than that of the equipment. To be effective, such protective devices must be properly located with respect to the equipment and adequately grounded.

10.3.2 Principles of Overvoltage Protective Devices

Assume that a surge appears on an energized conductor. The protection problem is how to get rid of the surge and how to restore the circuit to normal. What happens during the period the surge is being dissipated is also of interest.

Figure 10.15 shows a single-phase ac generator feeding a load through a transmission line. The generator includes a certain impedance designated as the power source impedance.

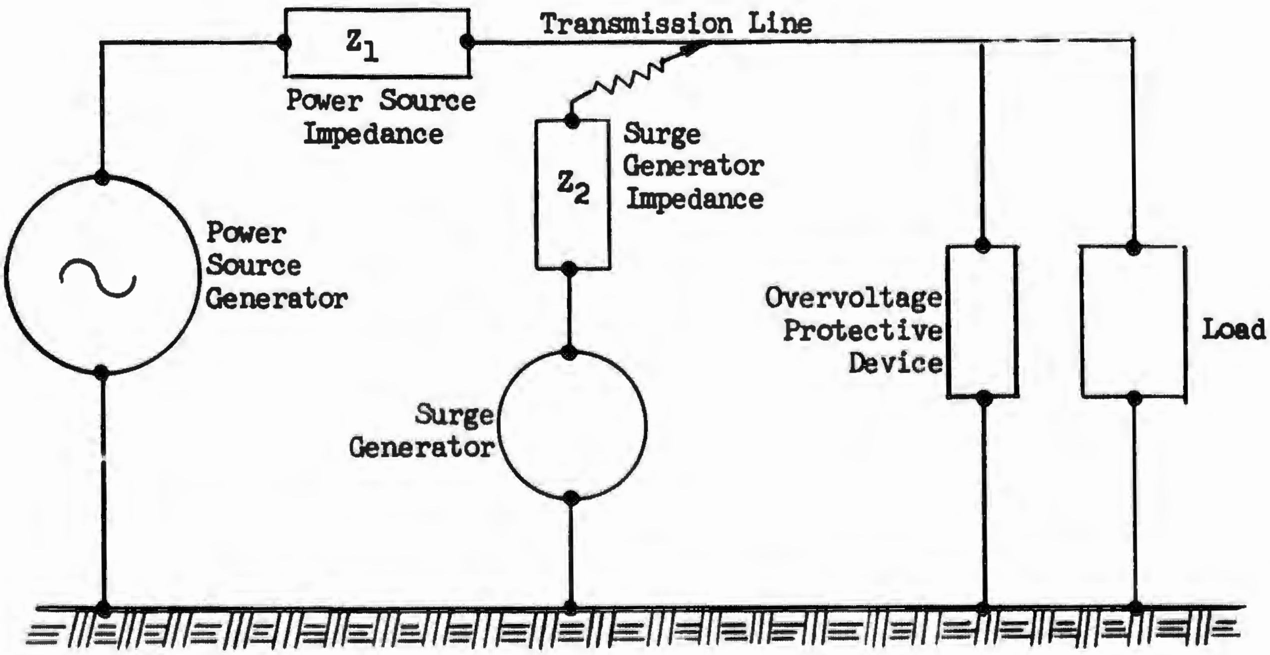


FIGURE 10.15 General Arrangement of Lightning Protection for Load at One End of Single Source Transmission Line

The surge generator introduces a high voltage surge (overvoltage transient) on the system. A circuit protector is placed on the system near the load for protection against surges.

The least sophisticated circuit protector would be a spark gap which consists essentially of several spaced electrodes surrounded by air or some other gaseous dielectric. A spark gap is generally adjusted to conduct when the voltage across its electrodes exceeds values less than those which the terminal apparatus (load equipment) could withstand.

With a spark gap, the first question that arises is the range of voltages over which it will sparkover (conduct). Sparkover voltage turns out to be very dependent upon gap shape, composition and pressure of the dielectric, and the wave shape of the applied voltage surge.

If the voltage wave is rising rapidly, the sparkover voltage will be higher than on a slowly rising wave. To illustrate this, Figure 10.16 shows three different input voltage wave fronts (e_1, e_2, and e_3) and the voltage and time at which the gap sparks. The dotted extension lines show the course the applied voltage would take if the spark gap were not present. Wave front e_1 represents a voltage that rises slowly, producing gap sparkover after a time, t_1, at voltage V_{s1}. A wave rising more slowly than e_1 would still cause gap sparkover at the same voltage, but after a longer time. A more rapidly rising voltage wave, e_2, would cause gap sparkover at a higher voltage, V_{s2}, but in a shorter time, t_2. Voltage wave e_3 rises yet more rapidly, resulting in a higher gap sparkover voltage V_{s3}, in still less time, t_3. A curve connecting sparkover voltage levels V_{s1}, V_{s2}, and V_{s3}, etc. at corresponding times of sparkover t_1, t_2, and t_3 is called the volt-time or time-lag characteristic of the spark gap.

In connection with the volt-time curve, Figure 10.16, the following points can be made:

1. For spark gaps in air, the long time sparkover voltage (V_{s1}) can not be less than about 300 volts.

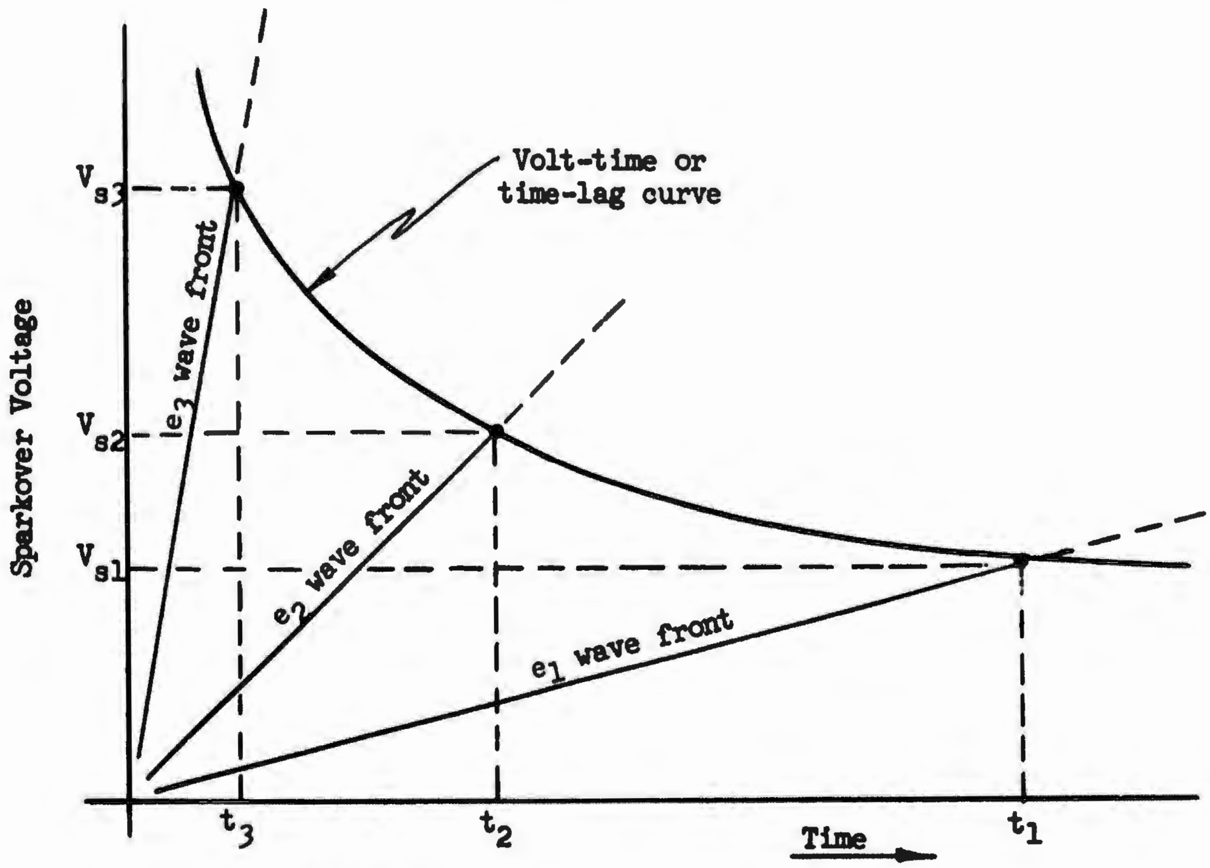


FIGURE 10.16 Volt-Time Curve for a Spark Gap

2. With practical gap spacings (those that can be maintained by adjustment in service) using metal electrodes and air at atmospheric pressure at the dielectric, V_{s1} is generally of the order of 1000 to 1500 volts.
3. The amount by which the sparkover voltage at short times exceeds the long time sparkover voltage (V_{s1}) is called the volt-time turn-up.
4. The greater the gap spacing, the greater the volt-time turn-up.
5. Gaps with non-uniform fields, i.e. sharp-edged gaps, exhibit more turn-up and have a lower long time sparkover voltage, V_{s1}, than do gaps with smooth contours and uniform fields.

6. Small gaps, of the type potentially suitable for protection of control and communication systems such as missile electronics, would show very little volt-time turn-up even at times of a few tenths of a microsecond.
7. Reducing the pressure of the air or gas dielectric lowers the long time sparkover voltage, V_{s1}, but increases the amount of volt-time turn-up proportionately. The time required for the spark to form increases as the gas pressure is decreased. Sparkover can be considered an avalanche ionization process; if the dielectric is less dense, the ionization potential to start the avalanche is lower, but more time is taken for ionization to reach a maximum.
8. Converse to 7, increasing the pressure increases V_s and decreases the volt-time turn-up proportionately.
9. By using gases (such as neon) instead of air as the gap dielectric, the long duration sparkover voltage, V_{s1}, can be made much smaller than 300 volts, but the volt-time turn-up will be increased proportionately. The addition of radioactive isotopes, such as krypton-85, to gas dielectrics will reduce the volt-time turn-up, stabilize the gap, and insure a precise, repetitive response.

Once ionization of the dielectric media of a spark gap is fully established, the gap impedance drops to comparatively low values, the spark conducts current, the gap maintains a practically constant low voltage across its electrodes, and the gap will not automatically deionize.

Refer to the circuit diagram shown in Figure 10.15. The current through a spark gap or other protective device will come partly from the surge and partly from the power source generator. The energy (W) dissipated as heat in the protective device will be the product of the total current (I), the arc drop voltage (V), and the duration of discharge (T).

$$W = IVT$$

This heat energy is exchanged, either by radiation and conduction to

nearby objects and/or absorption in the mass of the spark gap electrodes. The energy absorbed by the spark gap electrodes raises their temperature, and if the current is allowed to continue, the temperature will continue to rise until an equilibrium condition is reached. Then energy absorbed by the gap is equal to the energy carried away to its surroundings.

Energy developed as heat in a spark gap should be minimized and this can be done in several ways:

1. Keep the voltage across the electrodes low. Since the spark gap is a device which automatically switches to a low voltage state when it operates, it develops less heat energy than would a device which merely clamps a surge at a certain voltage level. On the other hand, with its inherently low arc resistance accompanying sparkover, it allows passage of more current than a clamping device.
2. Limit the fault current through the protector. The bulk of the current generally comes from the ac power source generator and not from the surge which made the protector operate. The greater the impedance between the protector and the power source generator, the better. For best overvoltage protection, the spark gap is best placed as close as possible to the load (assuming this is what is to be protected).
3. Limit the heat energy by interrupting the current through the gap as soon as possible after sparkover. In a spark gap this must be done externally by interrupting and keeping the follow current at zero until the gap dielectric has completely deionized. If the arc current is not interrupted, an ordinary spark gap will conduct continuously and the circuit cannot be returned to its normal state unless it is deenergized by external means, such as by opening a circuit breaker or blowing a fuse. A fuse must be replaced before the circuit can be restored. A circuit breaker can be reclosed

either manually or automatically, the latter taking a few cycles to a few tens of cycles, but in any case, there is sufficient time for the gap dielectric to deionize.

One way to interrupt the follow current is to partially enclose the spark gap in an insulating tube. With the arc partially confined, gas pressure builds up in the tube and the expanding gas cools and deionizes the arc. Sequence diagrams showing how such gaps operate to provide overvoltage protection for equipment are shown in Figure 10.17.

Another way to interrupt the follow current is to subject the arc at the spark gap electrodes to a magnetic field which, by motor action, causes the arc to move sideways into an insulating baffle which simultaneously lengthens and cools the arc until it extinguishes at a current zero. This principle is generally combined with the use of a non-linear resistance material in series with the gap. Such a combination is the basis of most valve-type surge arresters, Figure 10.18.

Sequence diagrams showing the steps in the operation of valve-type arresters are shown in Figure 10.19.

The non-linear resistance in a valve-type arrester is generally a material composed of silicon-carbide crystals in a suitable binder. It's General Electric trade name is Thyrite® and a generic term for it would be a varistor. It is made by several manufacturers. In this report, it will be referred to as a varistor for brevity.

In a varistor, the current is proportional to some power of the applied voltage.

$$I = KE^n, \quad \text{where}$$

K is the constant relating to the physical size of the varistor element and the exponent (n) is a constant relating to the composition of the varistor material. For Thyrite®, (n) is typically about four and may be as high as 7. If (n) = 4, doubling E will force 16 times as much current through the non-linear resistance element.

® Registered trademark of the General Electric Company

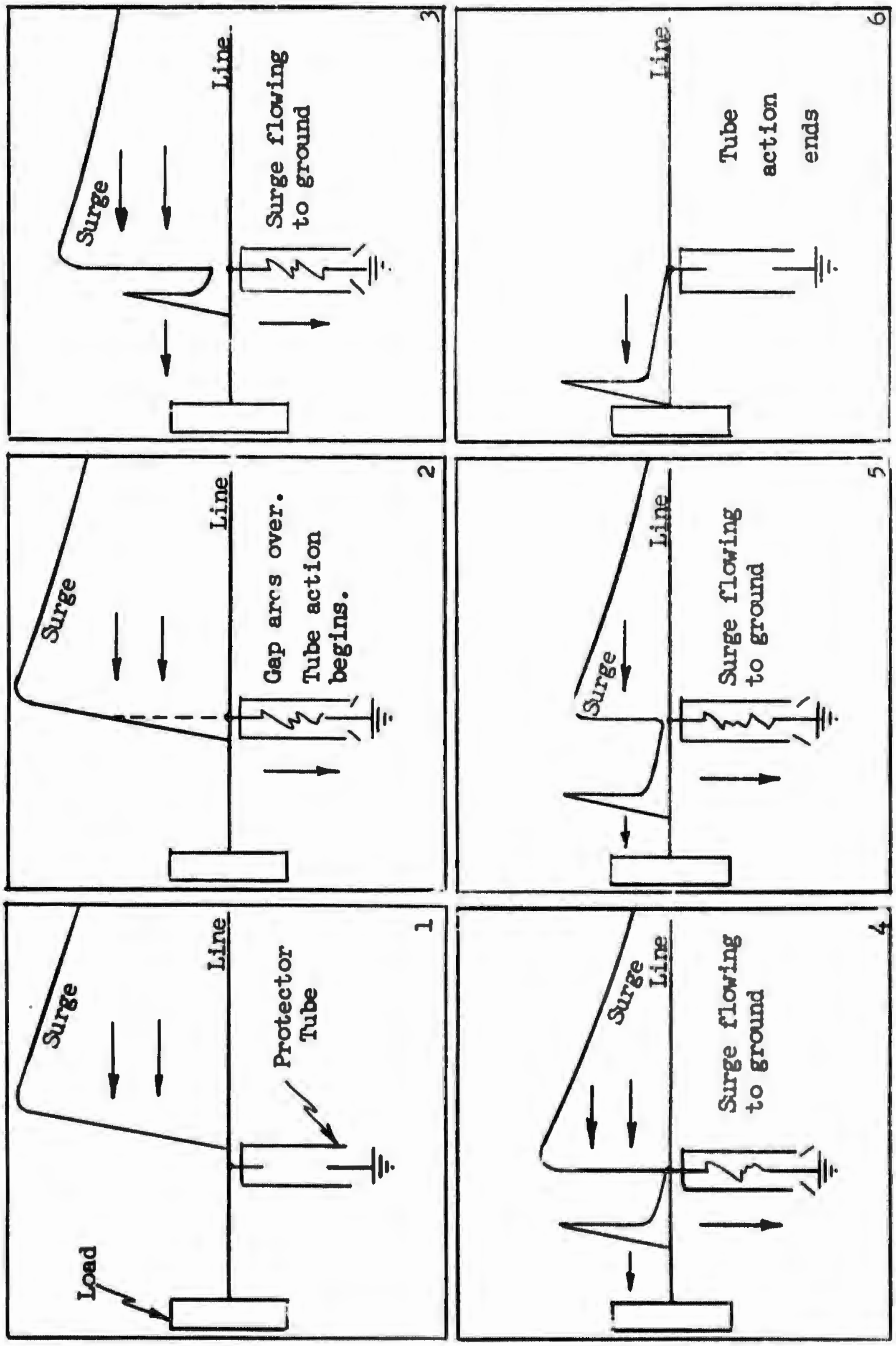


FIGURE 10.17 Sequence of Steps in the Operation of a Typical Tube-Type Arrester

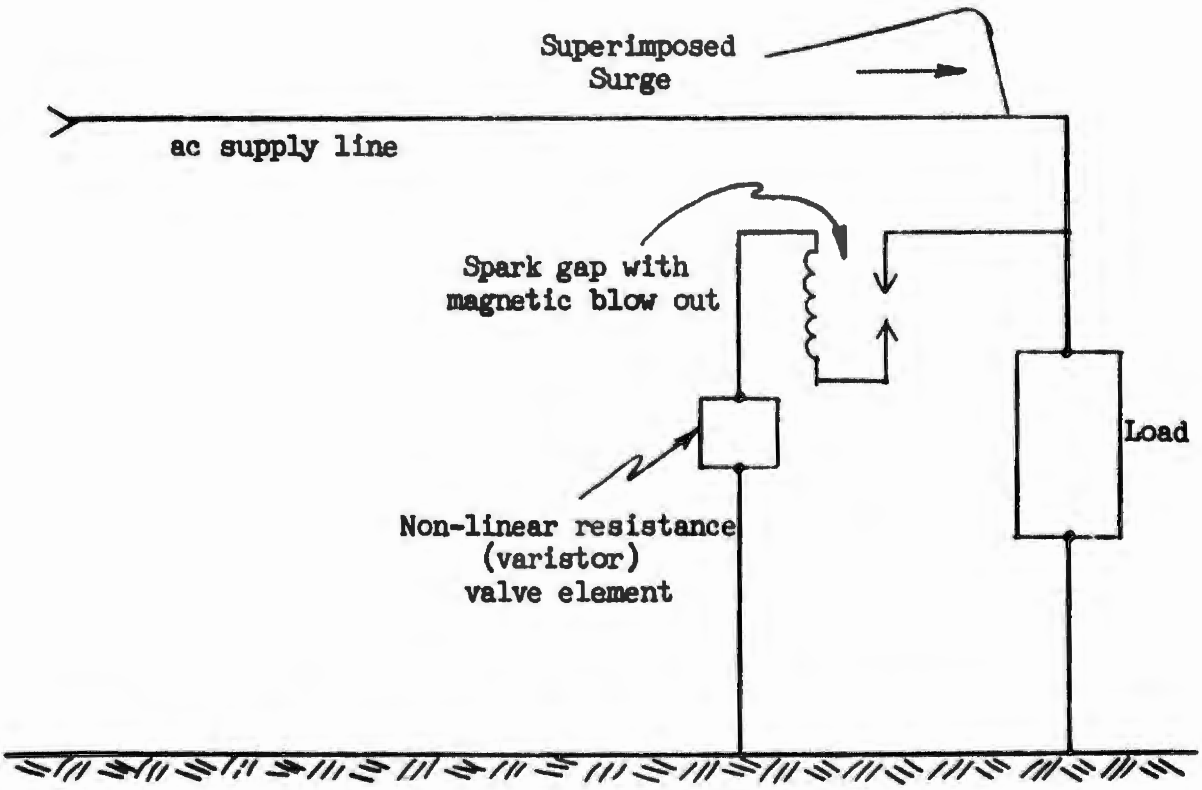


FIGURE 10.18   Basic Circuit Schematic for ac Valve-type Arrester

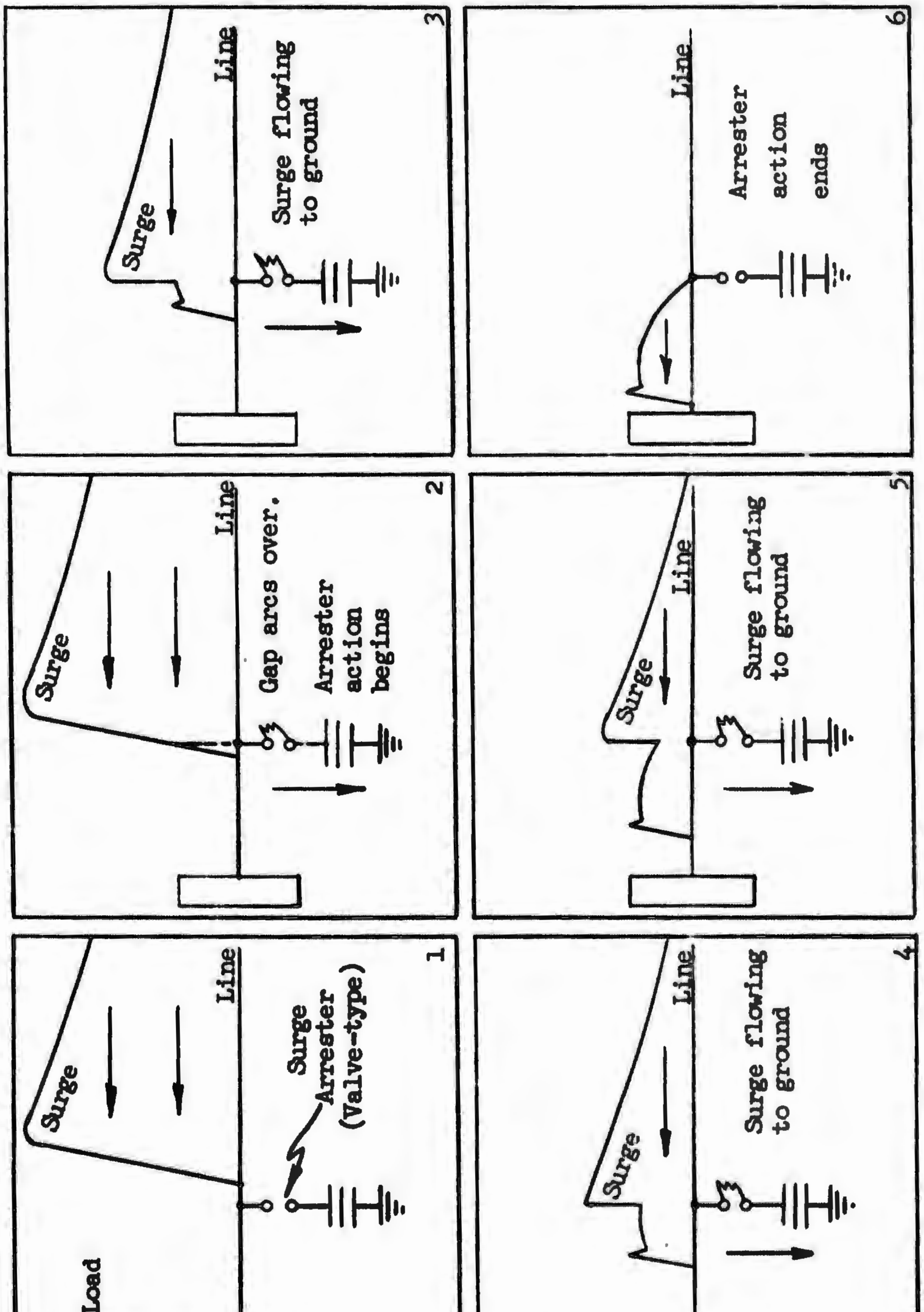


FIGURE 10.19 Sequence of Steps in the Operation of a Typical Valve-type Arrester

In designing a surge arrester for ac service, the varistor (valve-element) is chosen so that if the normal operating voltage of the circuit is impressed on the varistor (as would occur if the gap has been made to sparkover by a lightning surge), the follow current will be limited to such a low value that the arc across the gap extinguishes at the first current zero. This ability of the arrester gap to extinguish an arc by itself is called its "ability to reseal against the operating voltage". If the system disturbance caused by a surge is to be minimized, the surge protective device must have this ability to reseal. Most surge arresters have this ability. Plain spark gaps have no ability to reseal. Some kinds of protective devices using semiconductors in place of gaps have this ability, but some do not.

10.3.3 Surge Protection Devices for Control Circuits and Communications Systems

In general, control circuits and communication systems are operated at voltage levels considerably below those used for electric power work; therefore, the protective devices for these circuits need not handle the very large energies encountered at higher voltage levels. Some of the devices to be described here will handle large surges, but others are somewhat limited in their capabilities.

Protective devices acting as overvoltage suppressors for control circuits and communication systems may be listed under three categories, characterized by their mode of operation:

1. "Crowbar" devices or switches.
2. Voltage clippers and non-linear elements.
3. Linear energy storage elements.

1. <u>"Crowbar" Devices or Switches</u>

These devices operate by abruptly conducting or breaking down electrically when the voltage across them reaches a specified value. This action can be the result of the breakdown of a dielectric gas between two electrodes or avalanche or other solid-state phenomena across a semiconductor junction

or junctions. In general, devices employing breakdown of a gas can control high energy surges at the expense of rather loose tolerances on their protective voltage levels. Semiconductor devices can provide very tight control over voltage levels, but their thermal capacity to control surge energy is limited.

The breakdown or avalanche may either be directly triggered by the overvoltage so that the device appears as a two-terminal device, or be triggered by an auxiliary electrode (gate) in a three-terminal device with the triggering signal supplied by an adjustable voltage sensing circuit.

Many of these devices will continue to conduct after the initial triggering, so that external means must be supplied to interrupt the power current supplied by the steady-state voltage source after the disappearance of a triggering surge. This means that most generally, a serious disturbance is introduced in the system voltage until this power follow current can be interrupted. Some of the devices listed in Table 10.10 incorporate the interrupting means, but this feature is limited to ac applications. For dc circuits, a definite voltage interruption is required to stop power follow current.

The initial conduction or breakdown action of these devices is not instantaneous. As in the case of a spark gap, there is a relation between the time to breakdown and the rate at which the voltage is applied, with the result that the voltage to initiate conduction increases when the rate of voltage rise is increased. This is shown by the volt-time characteristic of a typical "crowbar" device, shown in Figure 10.20.

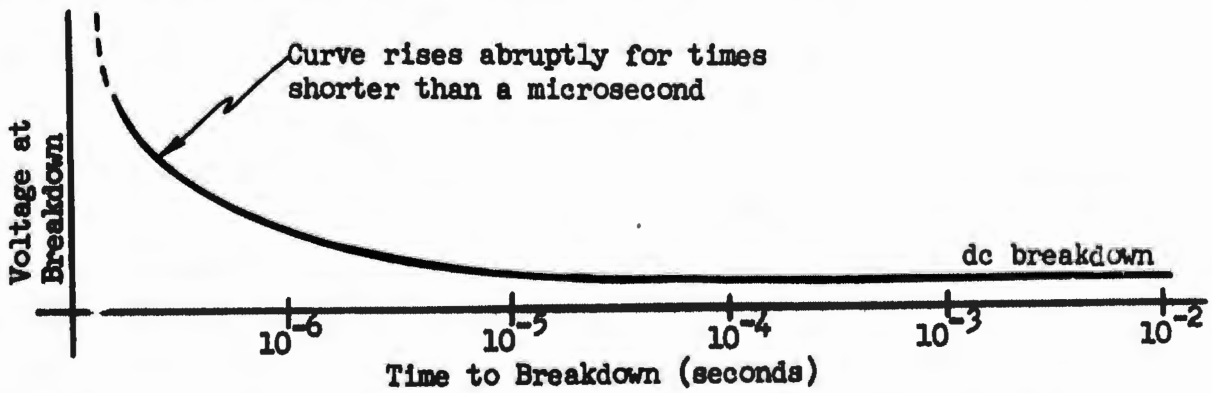


FIGURE 10.20 Volt-Time Characteristics for a "Crowbar" Device

TABLE 10.10

SUMMARY OF CHARACTERISTICS OF LOW VOLTAGE SURGE SUPPRESSORS

Minimum* Breakdown Voltage	Ratio of** Max. to Min. Breakdown Voltage	Peak Amps	Self Inter-rupting	Manufacturer and Type
250 to 6000	1.6	2000	No	General Electric Company 730 B
250	2.5	2000	No	AMARK Corp. Cerbersis UA1
800	unknown	3000	No	EG and G Corp. Fenotron
150 to 5000	unknown	unknown	No	Victoreen Inc. VX-96
750 to 50,000	unknown	1000 to 6000	No	Electronic Industries Series 43, 46, 47
230 to 800	unknown	unknown	No	Siemens Corp. surge voltage protector
500 to 2600	1.6 or greater	6000	No	Western Electric GA 51574, GA 51724
250 to 400	4	unknown	No	L M Ericsson Corp.
200	7.5	unknown	No	Amperex Corp. Model 0369
70 to 120	4	unknown	No	Neon Bulbs
1000	2.5	10,000	Yes	General Electric Company 9LA4C4
1000	4	5000	Yes	Westinghouse Corporation appliance protector
1500 to 5000	6	300	Yes	Dale Corp. LA-9

* Minimum overvoltage at which the protector will operate. Some manufacturers provide gaps for various voltages.

** Maximum breakdown voltage is defined as the 0.1 microsecond operating voltage.

The significance of this volt-time characteristic is that there is a time lag during which the "protective" device has no effect on the overvoltage. With steep-front surges, this can lead to high voltages left unsuppressed for durations of the order of a fraction of a microsecond until the device turns on. In this respect it parallels the volt-time characteristics of the simple spark gap discussed earlier.

Spark gaps, gas tubes, and semiconductor switches have both advantages and disadvantages. Some of these are listed as follows:

<u>Spark Gaps</u>

<u>Advantages</u>

1. Simple and reliable.
2. Easily fabricated.
3. High energy handling capacity.
4. Very low voltage drop (arc drop) during conducting state. When the gap is carrying maximum current, the voltage across the gap is typically 10-20 volts. If more current tries to flow, the arc channel increases in diameter and arc drop stays about the same. (A low arc drop indicates relatively low power absorption during the conducting phase.)
5. Bilateral operation - same characteristics on either polarity.
6. Fast response time - start conducting in less than one microsecond if well designed.
7. Zero power consumption on standby.
8. Wide operating range.
9. Long life expectancy.
10. Low internal capacitance.
11. Require no auxiliary equipment, power supply, or maintenance.
12. Relatively unaffected by radiation.

<u>Disadvantages</u>

1. Relatively high sparkover potential for their low-voltage ratings.

2. Simple gaps will not extinguish follow current. This is a most important point to consider if they are to be used on a power circuit. The arc must be extinguished externally be removing the voltage in some manner. This can be done by interrupting devices (circuit breakers or fuses), or by inserting resistance rapidly into the circuit by an additional element such as Thyrite®, or by gas-blast deionizers. By suitable design, spark gaps can be made self-extinguishing. Such self-extinguishing properties may make use of the magnetic blow-out principle or other means.
3. Spark gaps are seldom available in conveniently-packaged assemblies. They must be designed for each specific application. This situation is being improved.
4. Spark gaps in air are sensitive to variations in atmospheric conditions. Hermetically-sealed gaps do not have this disadvantage.

<u>Gas Tubes</u>

Neon, argon, krypton, zenon, and other gases ionizable at low pressure are often employed as dielectrics in low voltage spark gaps. Such devices can be used as surge suppressors, but their characteristics should be fully understood if they are to be properly applied.

<u>Advantages</u>

1. Low cost.
2. Small size (depending on bulb).
3. Low sparkover voltage - typically 60-100 volts in firing times greater than 2 μsec.
4. Can pass very high current for short time.
5. Self-healing (usually).

<u>Disadvantages</u>

1. Poor volt-time "turn-up" characteristics.
2. Will continue to conduct if the driving voltage is above 60-100 volts.

3. Possibly more sensitive to radiation than spark gaps in air at atmospheric pressure.
4. Will not absorb large amounts of energy.

Semiconductor Devices used as "crowbars"

These are semiconductors, such as Zener diodes, silicon-controlled rectifiers (SCR's), etc., which conduct abruptly upon avalanche breakdown or upon triggering. Since the impedance of these devices collapses to a very low value when they conduct, it is often necessary to add a series impedance in which surge energy can be dissipated and which, at the same time, limits the magnitude of power follow current. A non-linear resistor (varistor) such as silicon-carbide (Thyrite®) is very effective for this purpose. This material is used in commercial surge arresters.

Advantages

1. Good surge current ratings, although not as good as spark gaps.
2. Low voltage drop when conducting.
3. Suitable for use on low voltage dc circuits.
4. If properly applied, will interrupt follow current at the first power follow current zero following initiation of conduction.

Disadvantages

1. Low thermal capacity to dissipate surge energy.
2. Must be triggered by an auxiliary circuit.
3. Will not interrupt follow current on dc circuits.
4. Limited in rate of build-up of current or rate of build-up of voltage which can be tolerated.
5. Expensive.
6. Not bilateral. For protection on both polarities, two rectifiers and additional circuitry must be used. Bilateral devices are available. These are effectively two series SCR's back-to-back.

Descriptions of several types of commercial "crowbar" devices are as follows:

Mark I Engineering Semiconductor Protector (SCP)

This is a semiconductor "crowbar" device which turns on in a very short time. The specification calls for turn-on in less than 0.5 µs; one device tested showed turn-on times of 30 to 50 ns. The device could be set to exercise tight control over a dc voltage, although surges might rise to an excessively high voltage before the device turns on. In a previous study, a 30 volt SCP device started conducting on surges of 50 volts, but a surge rising at 40,000 volts per microsecond developed 1600 volts across the device before it turned on. This action is illustrated in Figure 10.20.

The basic device clears the circuit by blowing a fuse after it has been tripped by a surge. The manufacturer's specification sheet indicates that self-resetting models, and models to provide overcurrent protection, are available.

The specification sheet does not discuss the effects of an overvoltage surge of opposite polarity. For protection against surges of either polarity two devices might have to be used.

Dressen-Barnes Overvoltage Load Protector (OVLP)

This is another semiconductor "crowbar" device. It too shows a rapid turn-on time. It provides tight control over a dc voltage, but surges can build up to a high voltage before the device turns on. In this respect it is similar to the Mark I device. In the study mentioned above, the OVLP reached somewhat higher voltages than the SCP before it turned on.

T. I. Klixon Semiconductor Protector

This device combines a mechanical circuit breaker with a semiconductor "crowbar" device. It turns on slower than either the SCP or OVLP and allows even higher surge voltages to appear before it breaks down. Offsetting these disadvantages is its ability to interrupt follow current or overcurrents by means of its mechanical circuit breaker.

The device is polarized, with no comment from the manufacturer as to its performance with reverse polarity surges.

Dickson Series 1100, 1200, and 1300 Solid State Circuit Breakers

These devices are primarily designed for overcurrent protection, but can be used for overvoltage protection. They consist of a semiconductor series element and a semiconductor shunt element, the latter being primarily a sensing device. They provide overvoltage protection by sensing either the overvoltage directly or the overcurrent caused by the overvoltage. When overvoltage is sensed, the series circuit breaker opens, disconnecting the load from the incoming surge.

It will be noticed that this approach to overvoltage protection differs from the semiconductor "crowbar" devices. A point of concern is the overvoltage that could be tolerated with the series switch open without danger of "punch-through" of the open switch. An auxiliary protector might have to be used to limit surge voltages so that "punch-through" could not occur.

2. Voltage Clippers and Non-Linear Elements

Voltage clippers, as suggested by the name, limit rise of the circuit voltage above a specified threshold, generally by lowering their impedance in the same proportions that the voltage rises, with the result that the corresponding current causes about the same or a very slightly increased drop through the surge voltage source impedance.

Their effectiveness depends upon the ratio of their impedance under overvoltage conditions and the source impedance. The characteristic of these devices is best revealed through a plot of current versus voltage, which exhibits either a knee or a curvature as shown in Figure 10.21 in contrast with a linear resistor which would be represented by the straight line on this figure. Voltage clippers utilizing non-linear elements draw a small leakage current under steady-state conditions; this causes an energy dissipation which limits the steady-state voltage that may be

applied to the device. When an increasing amount of surge current flows through the device, the voltage across the device and the shunt-connected system to be protected rises slowly, as shown by the characteristic curve. It is apparent, however, that the voltage under surge conditions will, although limited, increase a significant percentage above the steady-state level.

Since clippers actually convert the surge energy within themselves into heat, their capacity is directly related to their capability of storing or rapidly dissipating thermal energy. On the other hand, as soon as the surge current decays and vanishes, they recover their normal impedance, so that a minimum of disturbance is introduced after the surge; their presence in the circuit is not significant under steady-state conditions.

Typical devices in this category include zener diodes, selenium rectifiers, and silicon carbide.

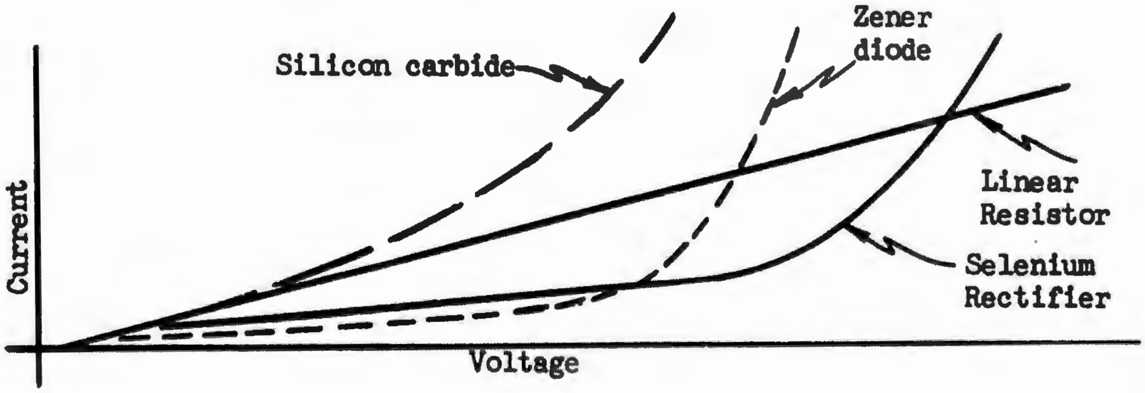


FIGURE 10.21 Performance Characteristics of Clippers and Linear Resistors

3. Linear Energy Storage Elements

Protective devices in this category consist of capacitors and ordinary resistors which may be used individually or in combination across the equipment.

Capacitors suppress overvoltage surges by temporarily storing surge energy which is gradually dissipated through the impedance of the equipment shunted by the capacitors; also the inherent distributed capacitance of long cables feeding equipment can cause a progressive reduction of wave front steepness of surges reaching the equipment.

Linear resistors are often employed across highly inductive dc circuits. These dissipate the stored energy of inductive elements.

Combinations of capacitors and resistors across equipment are also feasible. Energy in surges is momentarily stored in the capacitors, but dissipated at a predetermined decay rate dictated by the resistor. Such combinations are sometimes used to prevent excessive voltages at open switches accompanying surge reflection.

11.0 APPLICABLE DOCUMENTS

11.1 Associated Specifications

11.1.1 The primary specification governing the power system performance is the latest issue of the NIKE-X Power System Guidelines (U) classified SECRET - Restricted Data.

11.1.2 Dorris, M. C., et al, SYSTEMS ENGINEERING FOR THE CONTRACT PERIOD - FINAL REPORT (Bechtel Corporation, Vernon, California, November, 1965), Unclassified.

11.1.3 Other specifications to be identified.

11.2 Applicable Related Codes or Regulatious

11.2.1 Corps of Engineers Engineering Manual for Military Construction.

11.2.2 National Electrical Code.

11.2.3 National Electrical Manufacturers Association (NEMA).

11.2.4 American Standards Association (ASA).

11.2.5 MIL-STD-108E, Military Standard Definitions of and Basic Requirements for Enclosures for Electric and Electronic Equipment.

11.2.6 Institute of Electronic and Electrical Engineers Standards (IEEE).

11.2.7 Other codes and regulations.

11.3 Special NEMP References

11.3.1 Final Technical Report on Nuclear Electromagnetic Pulse Effects Research and Development Studies in Support of the NIKE-X Electrical Power System Program (U), (USAERDL, Fort Belvoir, Virginia, 5 November 1965), classified SECRET - Restricted Data.

11.3.2 Electromagnetic Pulse Phenomenology and Effects (U), DASA Data Center Special Report 41, classified SECRET - Restricted Data.

11.3.3 G739040 NIKE-X Weapons System Technical Requirements for Technical Facilities, 30 June 1966 or latest revision.

11.4 Order of Precedence

11.5 Deviations

11.6 Glossary of Terms

The following glossary is intended to clarify the meanings of certain terms within the context of these NEMP Protective Measures.

Armored Power Cable - electrical cable used for power circuit wiring having an outer interlocked armor construction and having each phase conductor insulation wrapped with a copper shielding tape.

Attenuation - reduction in magnitude of an electric or magnetic field, a current, or a voltage expressed in decibels, where

$$\text{attenuation (dB)} = 20 \log \frac{Q_1}{Q_2} \qquad \text{(see Section 5.3.1.1)}$$

Bonding Straps - a flexible wire or strap; used for bonding interconnections.

Cell Type of Construction - a double-walled metal room or building where the walls are internally connected by narrow strips of metal at discrete intervals.

Component Response - the voltage induced on electrical equipment in a given NEMP environment.

Conductivity - the reciprocal of resistivity (mho/meter, MKS).

Conduit - denotes rigid steel conduit, except where specifically designated otherwise.

Counterpoise - a continuous bare wire, or network, buried parallel to the earth's surface.

Decibel - a unit of attenuation (see Attenuation).

Dripproof (45 degrees) - a specification relating to enclosure design which conforms to definitions and requirements given in MIL-STD-108E.

Electrically Connected - having contact resistance less than 0.1 ohm.

Electrostatic Shield - a thin copper or aluminum grounded shield providing electric field shielding only.

Enclosure - refers to cabinet, room, or building which houses electrical equipment.

Fillet - a narrow band or steel plate.

Forced Air Ventilated - as defined in MIL-STD-108E.

Hardened Loads - electrical loads and distribution equipment capable of withstanding site environment.

Hertz - cycles per second.

Induced Voltage - voltage developed around a conducting loop by a varying magnetic flux linked by the loop.

Internal Grounding Ring - a continuous bare conductor around the inside walls of a building.

Injected Current - current which flows from a surrounding medium (earth).

Magnetic Field Environment - the azimuthal magnetic field at the surface of the earth.

Metal - any kind of metal.

Metal Coupons - buried metal samples periodically inspected for corrosion.

NEMP - nuclear electromagnetic pulse.

NEMP Environment - the electric and magnetic fields resulting from a nuclear detonation.

Non-hardened Loads - electrical loads and distribution equipments not expected to withstand site environment.

Non-metal - material incapable of conducting appreciable electric current.

Off-the-shelf - an item purchased from a manufacturer without alteration.

Over-pressure - the peak pressure in pounds per square inch from a given weapon yield.

Permeability (μ) - the ratio of the flux density (B) to the magnetic intensity (H). ($\mu = \mu_r\mu_o$), where (μ_o) = permeability of free space, equal to 12.57×10^{-7} henries/meter, MKS, and (μ_r) = relative permeability of a material.

Precise Power - power supplied to electric and electronic loads whose steady-state voltage and frequency requirements generally cannot be met by commercial electric utility systems.

Proof of Performance - test results or the unit meets government standards or military specifications.

Rebar - a steel rod used in reinforced concrete construction, commonly of materials such as (ASTM A15, ASTM A431, ASTM A432, and ASTM A408).

Relative Permeability (μ_r) - the ratio of the magnetic flux in a substance to the flux in air, the magnetomotive force and the geometry of the magnetic circuit being the same in both cases.

Resistivity - a measure of the resistance of a substance of a unit cross-section and of unit length (ohm/meter, MKS).

Rigid Steel Conduit - as defined in Article 346 of National Electrical Code, latest revision.

Shielding Degradation - a reduction of the shielding effectiveness in dB.

Shielding Effectiveness - the attenuation in dB provided by an enclosure, room, or building (see Attenuation).

Shielding Volume - the volume encompassed by shielding material.

Solid State - electrical equipment using components such as semiconductor diodes, transistors, etc.

Splashproof - a specification relating to motor and generator housings which conform to definitions and requirements given in MIL-STD-108E.

Trade Size - trade term denoting nominal diameter size of conduit.

Transient Overvoltage - a short duration voltage that exceeds the normal voltage rating of a circuit, component, or subsystem.

Utility Power - power supplied to electric and electronic loads whose steady-state voltage and frequency requirements generally can be met by modern, well-regulated commercial electric utility systems.

Wave Guide - a metal cylindrical or rectangular shaped tube, open at both ends, used to attenuate electric or magnetic fields.

12.0 BIBLIOGRAPHY

1. Dinger, D. B., FINAL TECHNICAL REPORT ON NUCLEAR ELECTROMAGNETIC PULSE EFFECTS RESEARCH AND DEVELOPMENT STUDIES IN SUPPORT OF THE NIKE-X ELECTRICAL POWER SYSTEM PROGRAM (U), USAERDL, Fort Belvoir, Virginia, 5 November 1965, SECRET-RD.

2. Uhlig, E. R., et al, TECHNICAL DATA FOR GENERAL NEMP DESIGN CRITERIA FOR NIKE-X POWER SYSTEM (U), General Electric Company, 5 August 1966, SECRET-RD.

3. Uhlig, E. R., et al, INTERIM SUMMARY REPORT, DEVELOPMENT OF DESIGN CRITERIA RELATING TO NEMP EFFECTS ON POWER SYSTEMS (U), General Electric Company, Pittsfield, Massachusetts, 5 September 1965, SECRET-RD.

4. Lux, R. A., NIKE-X ELECTRICAL SYSTEMS NUCLEAR ELECTROMAGNETIC ENVIRONMENT (U), General Electric Company, Pittsfield, Massachusetts, To be issued, SECRET-RD.

5. Rudenberg, R., GROUNDING PRINCIPLES AND PRACTICE, PART I: FUNDAMENTAL CONSIDERATIONS ON GROUND CURRENTS, Electrical Engineering, January, 1945, unclassified.

6. Dwight, H. B., CALCULATION OF RESISTANCES TO GROUND, Electrical Engineering, vol. 55, pp. 1319-1328, 1936, unclassified.

7. Sunde, E. O., EARTH CONDUCTOR EFFECTS IN TRANSMISSION SYSTEMS, D. Van Nostrand, New York, 1949, unclassified.

8. Watt, A. D., et al, SOME ELECTRICAL CHARACTERISTICS OF THE EARTH'S CRUST, Proceedings of the IEEE, vol 51, no. 6, pp. 897-910, June 1963, unclassified.

9. Lewis, W. W., THE PROTECTION OF TRANSMISSION LINES AGAINST LIGHTNING, Chapters 1 and 2, New York: John Wiley, 1950, unclassified.

10. Curdts, E. B., SOME OF THE FUNDAMENTAL ASPECTS OF GROUND RESISTANCE MEASUREMENTS, AIEE Transactions, vol. 77, Part I - Communications and Electronics, pp. 760-767, 1959, unclassified

11. Duke, C. A. and Smith, L. E., THE TECHNIQUE AND INSTRUMENTATION OF LOW IMPEDANCE GROUND MEASUREMENT, AIEE Conference Paper No. 58-105, unclassified.

12. MIL-B-5087A, BONDING: ELECTRICAL (FOR AIRCRAFT), unclassified.

13. Tinsley, E. C., GALVANIC SERIES OF METALS AS RELATED TO CORROSION, Rock Island Arsenal, February 1966, U. S. Department of Commerce Document AD 631962, unclassified.

14. Applegate, L. M., CATHODIC PROTECTION, New York: McGraw-Hill, 1960, unclassified.

15. Schwerdtfeger, W. J. and McDorman, O. N., POTENTIAL AND CURRENT REQUIREMENTS FOR CATHODIC PROTECTION OF STEEL IN SOILS, Research Paper 2233, J. Research NBS, August 1951, unclassified.

16. Ebasco Services, Inc., PRINCIPLES OF CORROSION AND CATHODIC PROTECTION, undated pamphlet, unclassified.

17. Thalman, E. H., SPECIFIC APPLICATION OF ZINC FOR CORROSION CONTROL, Address at 38th Annual Meeting American Zinc Institute, St. Louis, Missouri, 23 April 1956, unclassified.

18. Peabody, A. W., CATHODIC PROTECTION IN THE DESIGN OF POWER PLANTS, 20th Annual Conference of the National Association of Corrosion Engineers, Chicago, Illinois, 9-13 March 1964, unclassified.

19. Calvert, J. F., STUDIES IN SURGE PROTECTION, National Academy of Sciences Staff Working Paper, 9 March 1964, unclassified.

20. Dorris, M. C., et al, SYSTEMS ENGINEERING FOR THE CONTRACT PERIOD - FINAL REPORT, Bechtel Corporation, Vernon, California, November 1965, unclassified.

21. Medley, R. G., CORROSION CONSIDERATIONS IN THE DESIGN OF ELECTRICAL GROUNDING SYSTEMS, IEEE Paper, April 1964, unclassified.

13.0 PROTECTION TECHNIQUES AND METHODS INDEX

This index is a quick reference of protection techniques and methods for the power plant building and facilities with regard to the following subjects:

1. Control Room Shielding
2. Conduit
3. Electrical Wiring
4. Equipment
5. Enclosures
6. Grounding
7. Openings
8. Penetrations
9. Utility Piping
10. Power Plant Building Shielding

13.1 Control Room Shielding

13.2 Conduit

13.3 <u>Electrical Wiring</u>

13.4 Equipment

13.5 Enclosures

13.6 Grounding

13.7 Openings

13.8 Penetrations

13.9 Utility Piping

13.10 Power Plant Building Shielding